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The Warfighter Associate: Decision-Support and Metrics for Mission Command

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The Warfighter Associate: Decision-Support and Metrics for Mission Command

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14. ABSTRACT

This report describes a unique and promising intelligent agent plug-in technology for Mission Command Systems—the Warfighter Associate (WA)—that enables individuals and teams to respond more effectively to the cognitive challenges of Mission Command. The WA uses a doctrinally based knowledge representation to model role-specific workflows and continuously monitors the state of the operational environment to enable decision-support, delivering the right information to the right person at the right time. Capabilities include: (1) monitoring communications in chat rooms and other sources, (2) automatically plotting tactical graphics in a common operating picture, (3) reporting the current tactical situation, and (4) recommending courses of action (COAs) with respect to the necessary staff collaborations, re-tasking of assets, and required reporting. Specifically, two interrelated, hierarchical knowledge graphs based on the Observe, Orient, Decide, and Act (OODA) Loop model workflows and the state of the operational environment, facilitating doctrinally based recommendations for COAs based on available assets and asset capabilities. The knowledge graphs are state traces, measuring the staff cognitive demands across scenario runtimes as dynamic events unfold on the battlefield. Mission Command performance metrics can be automatically derived from the traces. Last, we discuss the potential of this technological approach to support Control and Command agility.

15. SUBJECT TERMS
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1. Introduction

Military operations are inherently complex human endeavors. Army commanders and their staff collectively face difficult and stressful challenges in managing battlefield operations. Warfare is chaotic and incredibly complicated and resolving the attendant ambiguity of the battlefield is a cognitive challenge of the first order. At critical times, Soldiers are under tremendous stress to quickly analyze overwhelming amounts of incomplete and sometimes contradictory data and to make decisions that have immediate impacts to mission success and human life. The consequences of those actions are not always intuitive or even predictable. In response to the complexity of the battlefield environment the current impulse and design of technical systems is to seek out and process more and more information (Lynch, 2008). To fully realize the benefits of technical systems requires that they are aligned with Soldier needs and capabilities (Bakdash, 2012).

Indeed, today's battlefield commanders and staff are inundated with huge amounts of information /intelligence that are pushed out, pulled in, and stored across increasingly sophisticated Army networks. One concern is that such a data rich environment can quickly overwhelm and paralyze human decision-making capabilities. Another concern is that human cognition is being reduced to managing complex computer databases and configuring displays at the expense of engaging higher-ordered human faculties of critical thinking, sense making, and reasoning about the battle space. A Vietnam-era commanding officer, COL Ted Fichtl (retired) who recently observed Mission Command at a Division and Brigade level exercise, turned aside and remarked, "My God! They've taken all the thinking out of Mission Command!" (Fichtl, 2010).

Managing the convergence of people, information, and technology—constituted as a *sociotechnical system* (Walker, et al., 2009)—is a defining challenge of our era. Despite the best intentions of solution providers there are inevitably situations where systems' capabilities are not in complete alignment with Soldiers' information needs. The inherent complexity and dynamic nature of military operations means there is an unbounded problem space: all possible intricacies involved in the dynamics of the Mission Command space and the interrelationships of technical systems are difficult to predict or specify. Researchers have difficulty capturing the intricacies of individual and team cognition particularly as Soldiers confront challenges with multiple overlapping problem spaces. Capturing and developing predictive performance-based models of such emergent problem solving behaviors is a difficult, if not intractable, challenge. System usability is a neglected but very important issue. Often systems are designed without a cognitive workflow analysis—or systems are used in unexpected ways—making them misaligned to critical user needs in a complex task domain.

This is important for aligning Soldier and system capabilities as user interface design, in general, tends to be feature-based, driven by the allure of technical capabilities rather than focused on supporting task execution. Interfaces and data exchanges with other systems can be challenging to fully understand during the design cycle. Network availability can hamper those exchanges. Lack of sufficient and regular training is a huge issue. Finally, as Soldiers and systems get deployed they face unconventional battle spaces and unanticipated enemy tactics; as a result new de facto requirements often emerge.

To address these information-age challenges it is imperative that systems are designed to present commanders and their staff with the "right" data in the proper format or context to address the urgency of the current situation and the critical decision at hand. A major tenet of the U.S. Office of Secretary of Defense's "data to decisions" initiative and a primary challenge for military commanders and their staff is to shorten the cycle time from data gathering to decisions. This report presents an Associate System that is designed to support Mission Command decision making. Such a system offers a novel class of automated metrics for assessing Soldier-system effectiveness; this constitutes a potentially important methodological breakthrough in capturing objective group performance. Metrics are essential to developing, evaluating, and improving Soldier-system interfaces and performance; and in our case, can also be collected unobtrusively. In this report, we describe an Associate System that supports the full sequence of "data to decisions" to ensure that it occurs in a timely and accurate manner and provides a novel class of metrics to assess the operational efficiency of Mission Command.

2. Overview: Associate Systems

2.1 Why an Associate System?

One potential solution to the problems of individual and staff overburden is a software plug-in known as an Associate System, and in our specific case, the *Warfighter Associate* (WA). Associate Systems are an implementation of fifth generation Artificial Intelligence (AI) technology called a knowledge-based system (KBS) (Arkerkar and Sajja, 2011). A KBS is an intelligent agent technology and uses collective knowledge from military doctrine, subject matter experts, and other information sources including users of the system. Compared to other types of AI technology several key advantages are conferred by the KBS of an Associate System, such as (Arkerkar and Sajja, 2011):

1. High degree of flexibility

2. Rationale for recommendations rooted in knowledge and available information

3. A proactive and reactive manner of operation

Flexibility is a key consideration for an AI system supporting military operations because of the frequency of uncertain and incomplete information and the dynamic operational environment. Moreover, by providing the underlying rationale for their recommendation, Associate Systems are transparent allowing users to see how the knowledge and information is being used by the KBS. This makes the technology much more suited for Mission Command than other AI approaches and allows users to provide feedback and refine and update the knowledge of the intelligent agent. Last, an Associate System is dynamic, updating with changes over time in the operational environment and using knowledge to make recommendations based on the current state of information and needs. Ultimately, these three characteristics are necessary for an AI system to be responsive to the uncertainty and complexity of information on today's battlefield and systematically tailored to staff workflows and the unit's standard operating procedures.

2.2 How Are Recommendations Generated?

To make timely and optimal recommendations the WA uses collective knowledge from doctrine and subject matter experts to infer human intention (goals) and reason about the best manner to achieve them (plans) given the state of the world (operational environment monitor). In addition, to maximize the flexibility of the WA, it is a plug-in capability and the WA knowledge is independent of the Mission Command System (MCS) it is integrated with. Thus, the system can run as a stand-alone application, or can be lightly and seamlessly integrated with current or future MCS.[*] To the extent that "rules" for developing an understanding of complex situations can be captured it makes sense to use software to provide this important adjunct to complex human cognitive problems. As a software plug-in, it can address issues that were not considered in the target system's design and can provide a complete set of knowledge to a new client solution.

2.3 Decision Support That Is Purposeful

Furthermore, the WA is dynamic. It is an intelligent system that actively collects and processes information, supporting multiple methods of problem solving, managing multiple levels of knowledge, adapting to real-world situations and even the user. Rather than taking the place of humans, the WA has been designed as a KBS that works hand-in-glove with a user as a helpful decision aid. The level of automation at which the WA operates is limited; it provides alerts, highlights critical information, and makes recommendations, but in no way removes decision making from the Soldier. Human interaction with automated systems can be formally defined into the following levels (Parasuraman et al., 2000):

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[*]A prerequisite for integration is that the MCS must have a well-developed application programming interface.

Levels of automation:

High   10. The computer decides everything, acts autonomously, ignoring the human.

     9. The computer acts and decides whether or not to inform the human.

     8. The computer acts and only informs the human if asked.

     7. The computer acts and then informs the human.

     6. The human has a limited amount of time to veto an automatic decision/action.

     5. The computer executes a human decision with approval.

     4. The computer suggests one alternative decision/action, the human must choose and act.

     3. The computer suggests multiple decisions/actions, the human must choose and act.

     2. The computer offers a complete set of decisions/actions, the human must choose and act.

None   1. The computer offers no assistance: the human must make all decisions/actions with no support.

The WA has a minimal level of automation (see the bolded **3.** on the levels of automation above); it suggests a set of specific courses of action but ultimately the decisions and actions are up to the Soldier. Rationale for the suggestions is provided to the Soldiers, for instance: the closest and best available intelligence, surveillance, and reconnaissance (ISR) resources in responding to a battlefield event based on a combination of availability, distance, speed, asset capabilities, and weather conditions. Transparency is a key system design requirement for achieving a high likelihood that a given recommendation will be accepted, selected, and acted upon by human operators (Parasuraman and Riley, 1997).

As an intelligent system, the WA is focused on supporting the user by augmenting performance and not by replacing him. This defines an Associate System in our vision of genuine Soldier-centered computing. As a guiding principle, Associate Systems assist the user by performing support tasks that are well suited for a computational system (rapid, simultaneous processing, and reasoning of large amounts of information in a dynamic environment), which can be particularly onerous for a human operator. For instance, Associate Systems can take full advantage of blazingly fast processing capabilities to quickly update and scour a database to support ongoing operations without needing a human user to specify the queries.

2.4   Driving the Mission Command Decision-Making Cycle

An Associate System is software driven by domain knowledge that is designed to work in conjunction with a human operator. It bridges the gap between highly autonomous systems that completely remove the human operator from the decision process and require perfect information and passive data access and presentation systems, which merely show the user the data what he requested. An Associate System can help to defeat enemies by enabling the Mission Command staff to engage in a high operations tempo by understanding their own decision cycle and reacting or pre-acting to their goals and can also provide possible insights into second- and third-order effects and unintended consequences. A relevant paradigm for Mission Command is the late Colonel John Boyd's concept of the Observe-Orient-Decide-Act (OODA) Loop (Boyd, 1986). The OODA loop defines a process by which an individual or team responds to a situation and related stimuli, with the need to repeatedly make decisions in light of dynamic events, and is closely related with the concept of Situation Awareness as developed by Mica Endsley (Endsley and Garland, 2009). In military circles, Boyd's theory is so encompassing—i.e., to include the processes of Mission Command, the ideas behind maneuver warfare, and a broad conceptualization of how to think about modern military operations—that it constitutes a major and defining theory of maneuver warfare (Polk, 1999). For our purpose of supporting decision making Boyd's theory is central in defining the essential cognitive cycle and collaborative dimensions of Mission Command *performance*, particularly in relation to an adversary. A concise conceptual summary of John Boyd's basic theory follows:

> Conflict can be seen as time-competitive observation-orientated-decision-action cycles. Each party to a conflict begins by observing. He observes himself, his physical surrounding and his enemy. On the basis of his observation, he orients, that is to say, he makes a mental image or "snapshot" of his situation. On the basis of this orientation, he makes a decision. He puts the decision in to effect, i.e., he acts. Then because he assumes his action has changed the situation, he observes again, and starts the process anew... With each action, the slower party's action is inappropriate by a larger time margin. Even though he desperately strives to do something that will work, each action is less useful than its predecessor; he falls further and further behind. Ultimately, he ceases to be effective. (Lind, 1985, pp 5−6)

Associate Systems can help humans across the spectrum of tasks associated with the dynamic situation assessment, planning, and acting cycle that is central to the OODA loop and the development of situation awareness (see figure 1). The OODA loop embraces a decision-making cycle that if left unsupported, would make it impossible to comprehend, shape, adapt to and in turn be shaped by an unfolding evolving reality that is uncertain, ever-changing, and unpredictable. Note in figure 1, how observation shapes orientation which supports both decision making and action; the whole decision-cycle is shaped by dynamic feedback loops

focusing and/or expanding our attention and observational window. A properly designed and implemented multi-agent intelligent system must be capable of representing knowledge relevant to all four stages in this process.
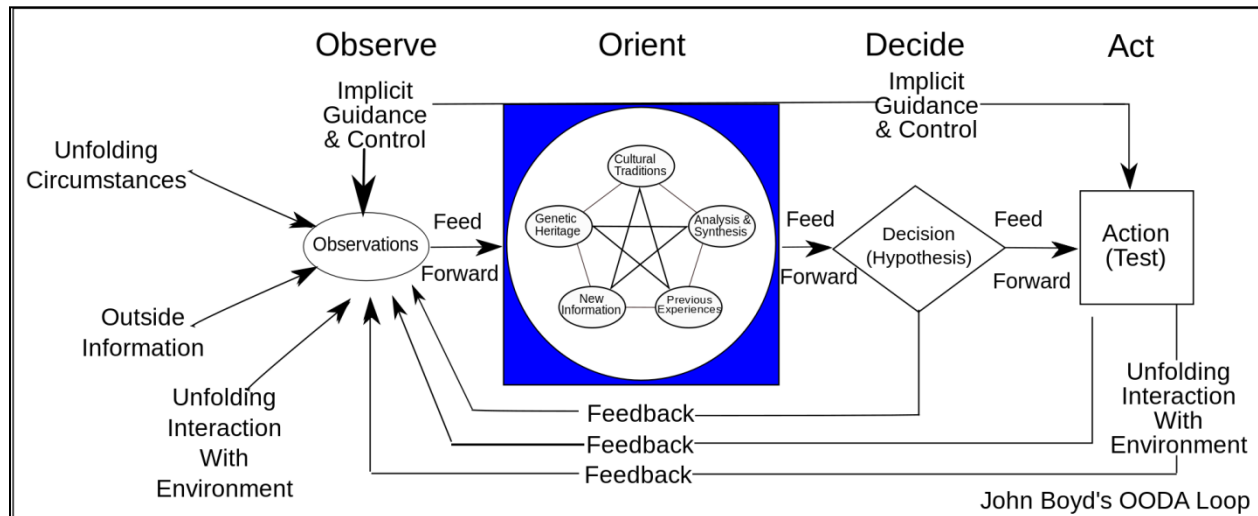
Figure 1. John Boyd's OODA Loop (adapted from Boyd [1986]).

The demands to human information processing, which involve observing and monitoring communication streams, as well as organizing, combining, and evaluating data and intelligence, can quickly overwhelm cognitive capabilities. The Mission Command work domain is an obvious candidate for computer support. The Associate both with and without human input can filter through vast amounts of data looking for information of importance to the user based on the user's intent. It does so by making abstract and aggregate conclusions about the state of the world, which normally requires both attention and expertise, in a more automated fashion. As information is being assessed the intelligent agent can help in the development of basic and advanced situation awareness, including the identification of patterns, correlation of different data, diagnoses, problem solving, and even goal setting; it can present to the user the "best" solution to this problem based on currently available information but support the user if a different course of action is chosen. In the action part of the cycle, the associate may be authorized to perform many of the routine tasks that could distract the user from the important events occurring. An Associate System also observes the actions undertaken by a human operator, combining those actions with the state of the world to determine the operator's current objectives and activities. Based on the assessment of the state of the world and the activities and objectives of the human operator, the system can, within the bounds of its authority, carry out activities on behalf of the user, make the user aware of events particularly relevant to his activities, recommend courses of action, and manage the information content of the user's displays.

The WA is intended to be a smart and seasoned assistant to the human user, designed to follow the human's lead, aiding whenever necessary without the need for explicit instructions and within its bounded discretion. The human user preserves all opportunities to interact normally and perform all system tasks completely manually. In the extreme, the associate could perform all of the system tasks autonomously (only if authorized)—although perhaps not with the fidelity of a competent, fully rested, and alert human user. The goal of the Associate System is to foster the functional integration of the sociotechnical Soldier system.

3. Associate Architecture

The WA is a software system that models tasks and task performance in complex real-time operational environments. The WA system was developed by Veloxiti Inc., (Alpharetta, GA) under contract with government partners: Communications-Electronics Research, Development and Engineering Center, and the U.S. Army Research Laboratory. The WA can be used both as a decision aiding system and as a normative model of task selection and performance by human users.

The WA is composed of a set of functions that create a closed loop cognitive engine that uses explicitly declared knowledge bases to perform situation assessment, dynamic planning, action execution, and coordination across multiple actors. Its main functions are as follows:

- *Situation assessment*. Data is received and organized into a hierarchical representation of the states of the environment. The hierarchy is defined by a knowledge base called the Observe-Orient (O-O) graph. The contents of the O-O knowledge base are implementation dependent and in the current versions of the WA as of the date of this report are being extended in a number of areas. As each new item of data is received the O-O graph is updated to reflect the current situation and the updates are logged into a file.

- *Dynamic planning*. Based on information provided in Operations Orders, as well as the ongoing expression of commander intent, the dynamic planning function manages multiple concurrent goals and determines activities required to satisfy the active goals. The dynamic planner uses a knowledge base known as the Decide-Act (D-A) graph to guide its selection of planned activities for the active goals. The dynamic planner is a managed commitment planner and it logs each state transition for each plan or goal instance over time.

- *Information management*. As the WA dynamic planner determines relevant plans and goals, monitoring requirements are posted to the situation assessment function. When monitor conditions are met events are sent back to the dynamic planner and notifications may be created to send to the user interface.

- *Coordination.* The WA is made to support multiple operators as members of a team, each with joint tasks, as well as his own tasks and responsibilities. To support this, the WA knowledge can define shared activities, shared goals, and shared concepts that can be sent directly from one running instance of WA to other running instances. Its knowledge can also be configured to detect conflicts in activities and goals between separate operators. Information can be shared at different levels of detail. For example, a conclusion about the world state can be shared without sharing the low level information on which it was based, conserving bandwidth and preserving information security.

The WA logs its internal transactions in terms of situation assessment, dynamic planning, information management, and coordination. The specific content of logged information is dependent on the knowledge bases used by the associate. A mature set of knowledge bases will typically provide a more complete set of logged transactions than a partial prototype set of knowledge bases. As noted above, the current WA knowledge bases can be expanded to include additional O-O and D-A nodes without disrupting its ability to log content.

3.1 System Features

Associate systems share a number of important architectural features that are the result of designed function integration with their human users. First and foremost, Associate Systems include a cognitive model that encapsulates the human decision-making process. The WA cognitive model has the following components that are common to associates:

- Domain-specific knowledge

- The ability to accept situational data as input data

- The ability to accept user actions as input data

- Algorithms to assess user actions, situational data, in accordance with the domain knowledge and do one or more of the following: provide notifications, provide suggestions, or perform system actions

Mastery of domain-knowledge engineering is a major enabler of an Associate System. It also takes full advantage of the fact that cognitive work flows are relatively constrained by the physics of the battlefield. That is, the decision space is fairly circumscribed by the overarching goals, mission objectives, and the sets of elemental actions and plans to achieve them. As a brief example, given a reported improvised explosive device (IED) event, the Associate System provides to the user—here, an intelligence officer (S2)—a recommended list of nearby surveillance assets that could be repositioned to quickly provide eyes on the event location. The Associate System's knowledge representation "knows" that in response to an IED event this given user is likely to want to reposition known nearby surveillance assets with particular known capabilities. The term "known" indicates that the Associate System is aware of the current state of the world, such as the position of and capabilities of the available surveillance assets. In this

manner, the Associate System is proactive in aligning the likely goals and decision-making authority of the warfighter with the means to achieve them (plans).

3.2   User Intent Interpretation Engine

A key to understanding the mechanics of the Associate System is to think of the gears of the process as a *user intent interpretation* engine. Observed actions drive the intent interpretation capability of the Associate. By observing the Warfighter's actions, the Associate can interpret which scripts the warfighter is following, allowing it to refine its user intent representation—the set of active plans and goals—so that it can support the warfighter based upon his actual intent, even if that intent differs from the associate's recommendations. Specifically, the capability to model the knowledge used to represent the decision-making process and to drive the behavior of the WA is provided by the Velox* Intelligent Software Suite. Figure 2 is a diagram of Velox.
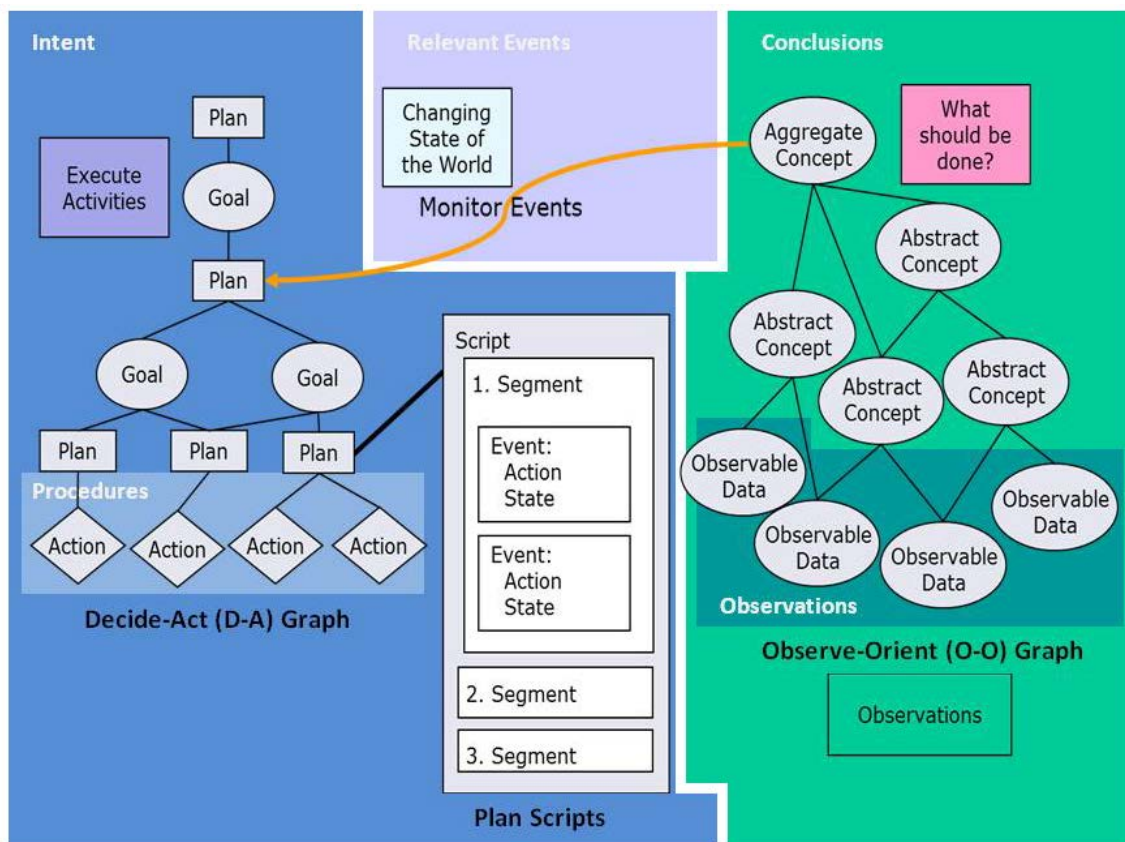
Figure 2. Velox Intelligent Software Suite with O-O and D-A graphs.

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*Velox is a trademark of Veloxity, Inc. (Alpharetta, GA).

3.3   Knowledge Structures

There are three related knowledge structures in the WA: the O-O graph, the D-A graph, and Scripted Plans that encapsulate procedural knowledge. The D-A graph is a model of means (plans) to achieve end states (goals). Plans require information about the current state of the world, and the O-O graph contains general, hierarchical knowledge about the world and is dynamically updated as the operational environment changes. Scripted Plans represent procedural knowledge—the specific set of steps to pursue a particular course of action. These three knowledge structures work together in a loop, the current state of the world is used to reason about plans, steps for plans are provided, and the execution of plans (recommended or not) can change the state of the world.

3.3.1 The O-O Graph

The second knowledge structure is the O-O graph. The O-O graph represents general and situational knowledge about the current world state ("who," "what," "when," and "how much"), and linkages among concepts represented. It is a depiction of and a structure for a hierarchical and dynamic description of the factual or perceived state of the world and can include many types of information (e.g., political, economic, and social data). The O-O graph provides a means for distinguishing between beliefs about the state of the environment and its true state. It also supports the representation of uncertain or evidential relationships between dynamic concepts by building belief nets using Bayesian logic. Beliefs are dynamically updated as a result of observations in the form of incoming data about the perceived state of some aspect of the environment; the updated situation awareness influences the Associate's purposeful interactions with the environment through the O-O graph. The links between the beliefs contain instructions for computing higher level aggregations and abstractions contained in each "parent" concept from the data contained within each "child" concept. Uncertainty calculations may also be contained in the links, allowing different sources of information to receive more or less influence in shaping the belief value of the concepts. For instance, in detecting IEDs remote sensing assets can capitalize on the strong correlation between latent thermal emissions and physical changes to soil to identify the nature of a disturbance as evidence of a threat. A reported "hot-spot" thermal signature on the ground (i.e., residual heat from a running vehicle that stopped for a period of time) constitutes weak evidence of an IED. However, if this is coupled with a report of "disturbed earth" at the same location, both sources of evidence contribute to a strong belief that there may be an IED. This would trigger the WA to notify the staff of a potential IED (PIED) by placing both a yellow (possible) IED icon on the tactical map, as well as a notification about the reasoning (hotspot and disturbed earth reports).

3.3.2 The D-A Graph

The first of the three main distinct knowledge structures is the D-A graph, which is a graphical depiction of the hierarchical task structure in the system being modeled. This structure allows a principled separation between the desired or intended future state or purpose (goal) from the means or method through which that goal might be attained (plan). It supports plan generation and plan recognition in dynamic, uncertain environments. A collection of goals and possible plans for achieving each goal makes up a course of action for a group. The D-A graph is defined to represent the alternative ways that goals can be achieved, so each plan child of a goal is a possible means to achieve the parent goal. Plan nodes are then decomposed into sub-goals, with decomposition in this manner continuing until the level of basic interactions is reached in the form of scripts. A D-A graph may provide for the intentions of many types of groups within a model. By observing the human's actions and interpreting them in the context of the task models in the D-A graph, the WA can infer the human's intentions by explaining them in terms of implied plans for achieving shared task goals. Implicit intent to switch tasks, strategies, or operational modes can be deduced through task-oriented behavior.

3.3.3 Monitoring Dynamics

To provide dynamic behavior to the model, nodes (Concepts, Plans, and Goals) have dynamic life cycle states. In the O-O graph life cycle state represents the prominence of a belief, allowing beliefs that are no longer supported by evidence to become forgotten. The life cycle states present the commitment status of a plan. For example, a plan instance describing a possible behavior may be under consideration by an individual or group but not yet fully defined or proposed. Once proposed, the plan may become accepted by the group, but may not be ready to start. The allowed life cycle states of a plan continue through execution, completion, and termination. The feasibility and desirability of any particular course of action (path through the D-A graph) will depend on what the group believes about the environment and what stage of development the group is in (O-O graph).

To implement the dynamic connection between the state of the environment and the possible courses of action, the model framework provides a concept monitoring mechanism. For example, a high-level plan "to survive" may subscribe to messages about threats. If an IED is reported the subscription monitor will fire, triggering planning. The group may consider multiple ways to accomplish a goal to diffuse the IED. The specific way selected will activate monitors for the relevant information in the O-O graph. For example, a plan to use the second Explosive Ordnance disposal platoon will monitor the O-O graph for obstacles on the route between the maneuvering platoon's location and the location of the IED. If a conditional statement in a monitor is found to be true the detected event may be used to transition a plan or goal to a different life cycle state. In this way, plans and goals that are no longer feasible or desirable can be discarded and replaced with more desirable ones as the state of the beliefs change over time and in different stages of the group development.

3.3.4 Procedural Knowledge: Scripted Plans

The third knowledge structure is Scripted Plans in the plan nodes of the D-A graph. Scripts contain the procedural knowledge and the steps to execute the actions. For example, with potential IED the WA does the following: displays a threat alert for Priority Information Requirements (PIR), displays the active threat in with IED indicator on the Area of Operations (AO) map, suggests cordoning off the area, recommends the most appropriate equipment for tactical cross cue, and queries the database for related other events related to IEDs. Note the procedure knowledge also depends on the role and responsibilities of the Soldier. The procedure knowledge structure is the mechanism through which the WA recommends courses of actions and helps with the interpretation of user intent.

The WA decomposes high-level, abstract plans into lower-level, more concrete plans. Eventually, all decisions are made, and a plan can then be executed by running a script. Velox scripts contain actions and logic to determine when each action is appropriate. Actions, which are manipulations of the world state, can be performed by the Associate ("performed action") or executed by the human and observed by the Associate ("observed action"). Because Associates are mixed initiative whether an action is performed or observed can be determined during runtime. Examples of actions include calling a route planner, querying a database, or re-tasking an asset. As a key part of the OODA loop, actions, by their definition, change the state of the world, which causes the O-O graph to be updated. This may result in re-planning, which may then cause additional actions to be performed.

4. WA Knowledge

4.1 Knowledge Engineering

Knowledge-engineering tools are used in developing and maintaining the O-O and D-A graphs and the associated plan scripts. These tools, integrated with Velox, enable doctrinal and subject matter expert knowledge to be easily entered and put into a format where it can drive WA behavior. For the WA, the O-O and D-A graphs and the plan scripts are a model of many of the complex and messy situations that Mission Command staffs face, along with appropriate doctrinal and subject matter knowledge that reflects desired task actions and synchronization. The knowledge comes from approximately 20 different Army publications, as well as subject matter expertise in response to high-intensity events, such as IED detonations, medical evacuation (MEDEVAC) operations, high value target (HVT) sightings, Restricted Operating Zone (ROZ) establishment, and so on (see figure 3).

4.2 Agile Knowledge Development

The Knowledge Engineering tools that are part of the WA enable doctrine or subject matter expertise to be added or modified within the knowledge base. The system is deliberately engineered to permit the agile development of the knowledge; the knowledge can be changed without requiring any changes to the underlying software or system architecture. The O-O and D-A graphs sit on top of the associate architecture and, thus, are readily modifiable, for instance to tailor the knowledge to a Commander's standard operating procedures or to evolving threats on the battlefield. As a separate research effort (under the Tactical Human Integration of Networked Knowledge - Army Technical Objective), the existing Knowledge Engineering environment and tool suite is being modified with the goal of letting responsible military personnel, with minimal training, model or make modifications to existing models of complex tasks to tailor system performance to perhaps a specific situation arising out of their workflow. This enhanced capability will make modifying the knowledge in response to Standing Operating Procedures or newly discovered Tactics, Techniques, and Procedures more feasible and contribute greatly to the ability of Soldiers to manifest *agility* in our technical systems.
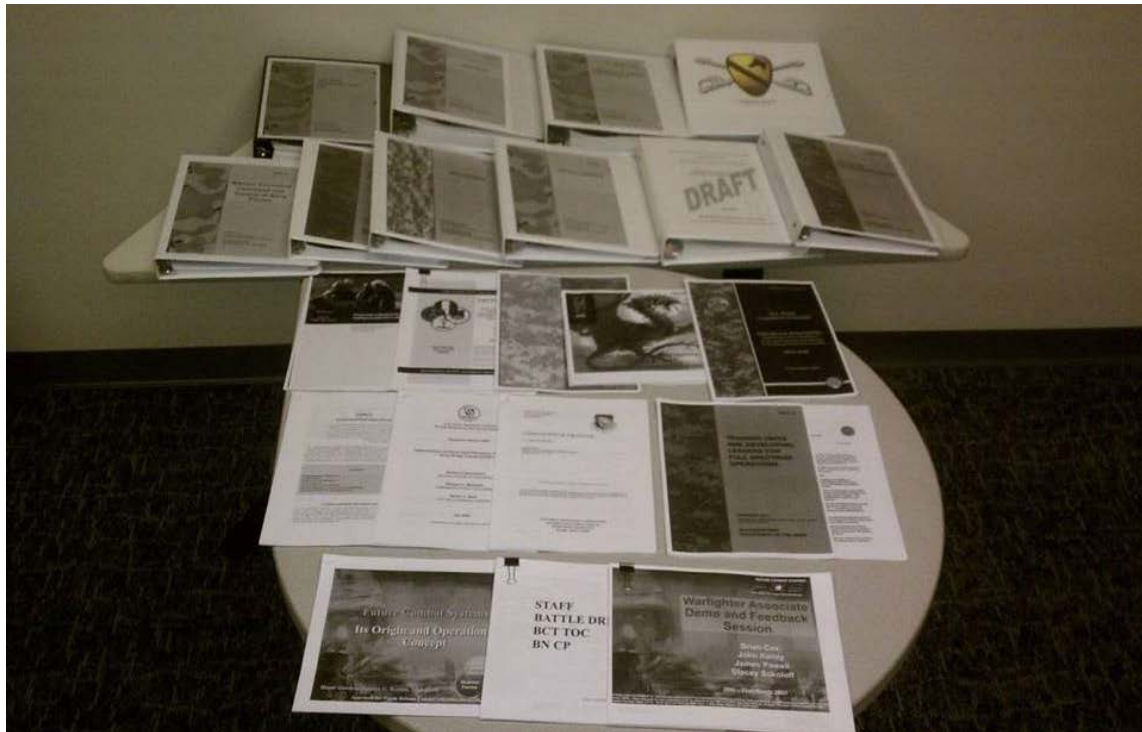
Figure 3. Army publications used in current Knowledge-Engineering build of WA.

5.   The Warfighter Associate in Action

A central tenet of OODA loop theory is that a high operations tempo allows one to outpace the adversary and, thus, gain the initiative by getting "inside" of the enemy's decision-making cycle. In this section, we illustrate how information from the communications network is pulled into the WA to activate a doctrinal knowledge base to push support for warfighter decision making at the various phases of Boyd's military decision-making cycle—the OODA loop. We will demonstrate how the WA supports each phase of this decision-making cycle in responding to battlefield events. Our goal is to develop an Associate System capable of supporting the Mission Command staff in maintaining a high operations tempo. We have constructed a short demonstration vignette to describe how the WA supports each phase of the decision-making cycle, notionally based on common battlefield events.

5.1   Tailored to Individual Role Positions and Facilitates Collective Action

The WA operates both at the role-specific level (critical tasks) and facilitates collective action (information sharing and collaboration). The WA supports key functions of the Mission Command staff in responding to significant battlefield events. Currently, three WAs have been developed for critical role positions at the brigade level—the maneuver officer (S3), the intelligence officer (S2), and the fire-support officer (FSO). These role positions were selected because of the importance of these role positions to the Mission Command network. In a recent field study of Mission Command at the Division and Brigade levels, social network analyses of communications data identified these role positions (S3-S2-FSO) as central points of convergence during network-enabled operations for managing information and decision making (Buchler, 2011). Given the heavy cognitive workloads reported by the S3-S2-FSO role positions it is also likely that these individuals would have most to gain from using associate technology. Each built "instance" of the WA (i.e., S3, S2, FSO) supports the task-specific requirements of that duty position, and these software agents communicate with one another to facilitate situational understanding and collective action. In table 1 we provide a detailed description of the WA in action. Below we describe how the WA provides support to drive the four phases of the decision-making cycle on an existing Army MCS, the Command Post of the Future (CPOF).[*]

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[*]The Warfighter Associate is system not tied to any MCS and can be leveraged to work with any of the existing or future MCS.

Table 1. Vignette example of the WA.

Chatroom Dialogue	Time	WA (Role Specific)			Node	Type
		S3	S2	FSO		
"High value target (HVT) the Dentist located at [*grid*]"	0:00	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3	S2	FSO	View Area	Action
		—	S2	—	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	—	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		S3		—	Issue SPOT Report	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events (related to HVT)	Action
"Troops in contact TIC at [*grid*]"	9:08	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3			Deploy to Cover	Plan Proposal
		S3	S2	FSO	View Area	Action
		S3	—	—	No ISR Asset Covering Threat	Notification
		—	S2	—	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	—	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		S3	—	—	Issue RFI	Action
		S3	—	—	Issue SPOT Report	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
"Demonstration at [*grid*]"	11:37	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3	—	—	Cordon Area	Plan Proposal
		S3	—	—	Use PSYOP	Plan Proposal
		S3	—	—	Coordinate with Host Nation Police	Plan Proposal
		S3	S2	FSO	View Area	Action
		—	S2	—	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	—	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		S3	—	—	Issue RFI	Action
		S3	—	—	Issue SPOT Report	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
"Hotspot reported at [*grid*]"	14:03	—	—	—	—	—

Table 1. Vignette example of the WA (continued).

Chatroom Dialogue	Time	WA (Role Specific)			Node	Type
"Potential IED (PIED) a [*hotspot grid*]"	15:14	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3	S2	FSO	IED Indicator in AO	Notification
		S3	—	—	Cordon Area	Plan Proposal
		S3	S2	FSO	View Area	Action
		S3	—	—	No ISR Asset Covering Threat	Notification
		—	S2	—	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	—	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events (related to IEDs)	Action
"IED at [*hotspot grid*]"	16:41	S3	S2	FSO	Threat for PIR	Notification
		—	S2	—	Active Threat in AO	Notification
		S3	—	—	Issue RFI	Action
		S3	—	—	Issue SPOT Report	Action
"The Dentist seen at [*new grid*]"	18:46	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3	S2	FSO	View Area	Action
		S3	—	—	No ISR Asset Covering Threat	Notification
		—	S2	—	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	—	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		S3	—	—	Issue SPOT Report	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
		S3	S2	FSO	Active Threat in AO	Notification
		S3	—	—	Issue RFI	Action
		S3	—	—	Issue SPOT Report	Action
		S3	S2	FSO	View Area	Action
		—	S2	FSO	Use Most Appropriate Equipment for Tactical Cross Cue	Plan Proposal
		—	S2	FSO	Use Equipment In Area for Tactical Cross Cue	Plan Proposal
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action

Table 1. Vignette example of the WA (continued).

Chatroom Dialogue	Time	WA (Role Specific)			Node	Type
"MEDEVAC [*grid*] 1 urgent 2 routine 3 convenience"	22:38	S3	S2	FSO	View Area	Action
		S3	S2	FSO	MEDEVAC Needed	Notification
		S3	—	—	Designate Recovery Site	Plan Proposal
		S3	—	—	Cordon Area	Plan Proposal
"IED at [*previous grid*] resolved"	25:08	S3	S2	FSO	Cancel Event	Notification
		—	S2	—	Cancel Most Appropriate Equipment	Notification
		S3	S2	FSO	View Area	Action
"The Dentist spotted at [*new grid near Demonstration*]"	28:48	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Contextual Event	Notification
		S3	—	FSO	Active Threat in AO	Notification
		S3	—	—	Issue SPOT Report	Action
		—	S2	—	Insurgent Leader Near Event Location	Notification
		S3	S2	FSO	View Area	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
"HVT spotted at [*grid coordinates*]"	32:55	S3	S2	FSO	Threat for PIR	Notification
		S3	S2	FSO	Expiration (of earlier location)	Notification
		S3	S2	FSO	Active Threat in AO	Notification
		S3	S2	FSO	View Area	Action
		S3	—	—	Issue SPOT report	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
"SA-7 sighted at [*grid coordinates*]"	35:33	S3	S2	FSO	Equipment Matches NAI Based PIR	Notification
		S3	S2	FSO	View Area	Action
		—	S2	—	Provide Context	Plan Proposal
		—	S2	—	Query Database for Events	Action
"Demonstration at [*previous grid coordinates*] over"	37:47	S3	S2	FSO	Cancel Event	Notification
		S3	S2	FSO	Cancel Most Appropriate Equipment	Notification
		S3	S2	FSO	View Area	Action

5.2 Cycling Through the OODA Loop

5.2.1 Observe (Data Gathering)

For the Mission Command staff engaged in network-enabled operations, the *observe* function requires attending to all of the information inputs communicated across the network at a given point in time. A challenge presented by network-enabled operations is that the number of inputs into the network is rapidly outstripping the ability of any one person, or even perhaps a collection of individuals, to monitor them all. It is not uncommon for the Mission Command staff to monitor inputs from multiple chat rooms; one Operation Iraqi Freedom combat aviator

recounted routinely monitoring eighteen chat rooms and radio chatter all while piloting a rotary aircraft. A game-changing capability of the WA is its ability to simultaneously monitor *all* of the chat rooms. That is, although the processing capacity of human attention is limited to about 4 ± 1 units (or "chunks") of information at any given time (for a review, see Cowan, 2001), computers do not have this limitation. With a given knowledge processing system and sufficient computational power there is fundamentally *no limit* to the number of chat rooms or computer transcriptions of voice communications that an Associate System can actively monitor.

The WA learns about incidents either from a tactical spot report[*] or from a chat message. Note that chat room inputs on the network may be information relayed from radio telephone operators or aviators, both of whom provide vital communications links between units out in the field and headquarters. Chat is a primary input to the WA. The WA filters through the volumes of chat dialogue for key pieces of information using natural language processing. In response to a key piece of information, the WA will generate a monitor event (belief) on the O-O graph that will trigger nodes in the D-A graph.

Our vignette begins with input from one of the chat rooms that a HVT with the moniker "The Dentist" is reportedly in the AO. How the WA responds to observed chat inputs is detailed in table 1. The observe part of the cycle can be construed as the amount of time it takes to notice new inputs on the network, in this case, information relayed in chat room dialogue about a high value target. With the large number of chat rooms, a human operator could take a long time to notice, or entirely miss an input. In theory, the WA would not miss an input and should be consistently fast in relaying information.

5.2.2 Orientation (Situation Understanding)

The *orientation* phase is perhaps the most critical part of the decision-making cycle, because it shapes the way we interpret the situation. Boyd (1986) adds that "… without orientation there is no command and control worthy of the name… Orientation shapes the way we interact with the environment—hence the way we observe, decide, and act" (as cited by Polk, 1999). Boyd understood that mental models are central to understanding how an individual or group orients to the external environment. It is a frame of mind that determines how information is understood and synthesized into new or existing mental models of the situation. With proper orientation, individuals and the Mission Command staff may develop and maintain an accurate understanding —a current mental model—of events transpiring on the battlefield, what is termed individual situational awareness and a common shared understanding. Next, we describe how the WA orients the Mission Command staff to critical battlefield events in our vignette (table 1).

Using natural language processing of the chat room inputs, the WA recognizes that information pulled from a chat room concerns a HVT. This information, in turn, matches one of the

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[*]By monitoring chat it is possible for the Warfighter Associate to discover incidents several minutes before the report is physically posted and entered in MCS.

commander's PIRs. PIRs are an intelligence requirement, stated as a priority for intelligence support that the commander and staff need to understand the adversary or the operational environment (U.S. Army, 2006). An example of one PIR among a handful on a list could be: "*Identity and location of religious/political/tribal leaders who oppose our presence in the area of operations.*" PIRs are a key tool for the commander to establish priorities for the allocation of limited resources and to "dictate the employment of collection assets, analysis resources and should meter the flow of information within the headquarters" (Luck and Findlay, 2007). The activation of the WA is tied to the PIRs to ensure a commander -centric orientation.[*] The underlying knowledge representation enables flexibility in pursuing commander-centric aims. For instance, a potentially different constellation of plans and goals would be invoked from various chat room inputs if the commander were to shift the focus of his PIRs from an enemy-focused orientation to one that heavily emphasizes the security environment and supporting the local population. In this manner, the WA enables an agile response as well as adhering to and enabling a commander-centric orientation.

One of the functions of the O-O graph is to filter through information and to trigger goals that pursue command intent. The data concerning the HVT report is sent to the O-O graph, where it is assessed for relevancy, status, and location. In this example, the HVT is matched to the commander's PIR triggering the concept node *<Threat for PIR>* for all instances of the WA (S3, S2, and FSO). As the grid location of the HVT threat is within the boundaries of the AO, this triggers the O-O node *<Active Threat in AO>*. The end result is that all three role-players (and the entire Mission Command staff) are notified that a high-valued target has been reported in the area of operations. In figures 4, 5, and 6 the WA is used as a plug-in capability for the CPOF. CPOF is an MCS for sharing information and mission planning. The WA is integrated into CPOF the graphical user interface, manipulated to orient the Mission Command staff to this new event.[†] An HVT icon is mapped on the common operational picture— the "battle map"—with the appropriate information fields filled in and highlighted with a command and control (C2) pointer (purple arrow).[‡] The C2 pointer is an important feature for alerting the Mission Command staff to time and location sensitive events that have just transpired, minimizing the need for a visual search across the map display which can quickly become cluttered. In addition

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[*]The PIRs are developed by the commander and are a clear expression of command intent and can assist the staff in making decisions and recommendations. The success or failure of a mission can depend on the selection of PIRs as they are time-sensitive and directly supporting and driving key decision-points during mission executions. The appropriate selection of PIRs is vital to the art of command—too broad results in a deluge of information whereas too tight a specification does little to focus support on the mission.

[†]The user interface manipulations described are prototypes, but they have been exercised by Soldiers during experimentation in our laboratory. The Warfighter Associate can support any number of interface solutions to provide relevant information to the user in any MCS. Our solution is focused on the CPOF and providing the information in three dashboard panels (i.e., "stickies") that list "Recent Events," "Recommendations," and "PIRs" hits on the Commander's Critical Information Requirements.

[‡]It is important to note that the Warfighter Associate maintains a human-in-the-loop for decision-making and is not making a decision for a particular user. A more accurate description is that the Warfighter Associate provides a decision template to guide timely appropriate action. At times, many battlefield events can occur simultaneously and quickly overwhelm the decision cycle for a particular role-position—in such situations the Warfighter Associate may provide a useful performance floor to ensure a timely and coherent Mission Command response.

to updating the map, the WA populates the pink, yellow, and green boxes (right side) with role-specific information on the current situation, courses of action COA recommendations, and active commander's critical information requirements (CCIRs) or PIRs.
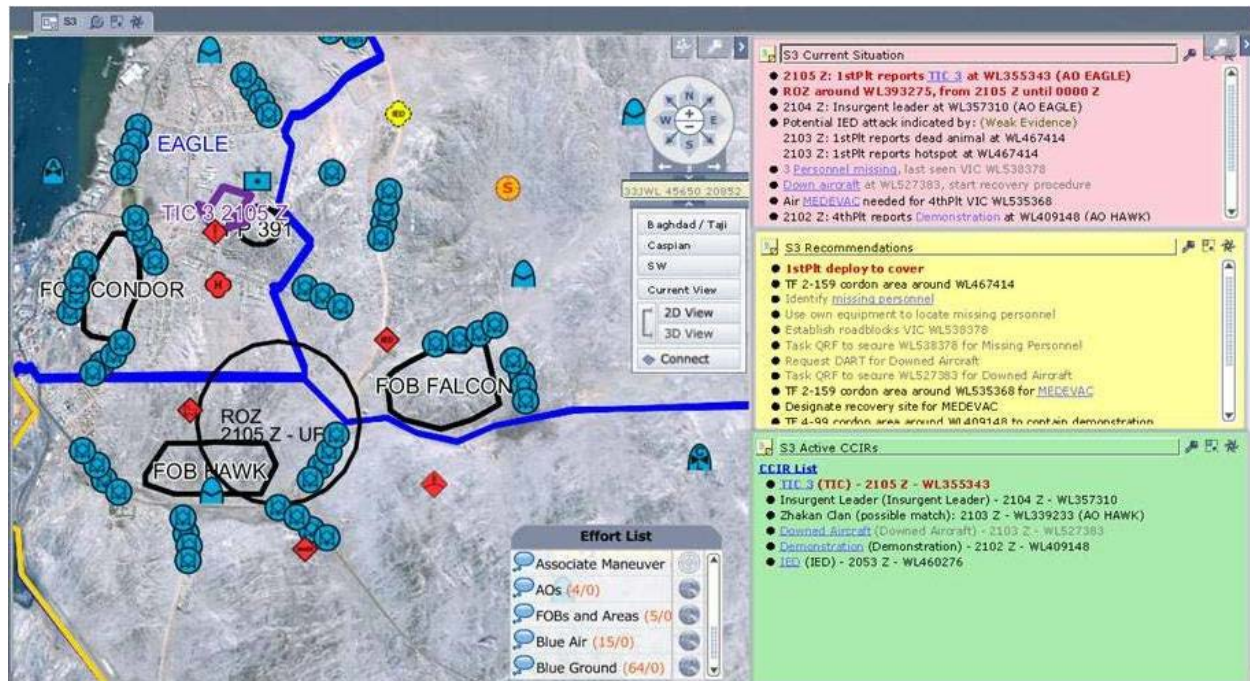

Figure 4. WA screenshot for the Operations Officer (S3) as implemented on the CPOF–Army Mission Command System.
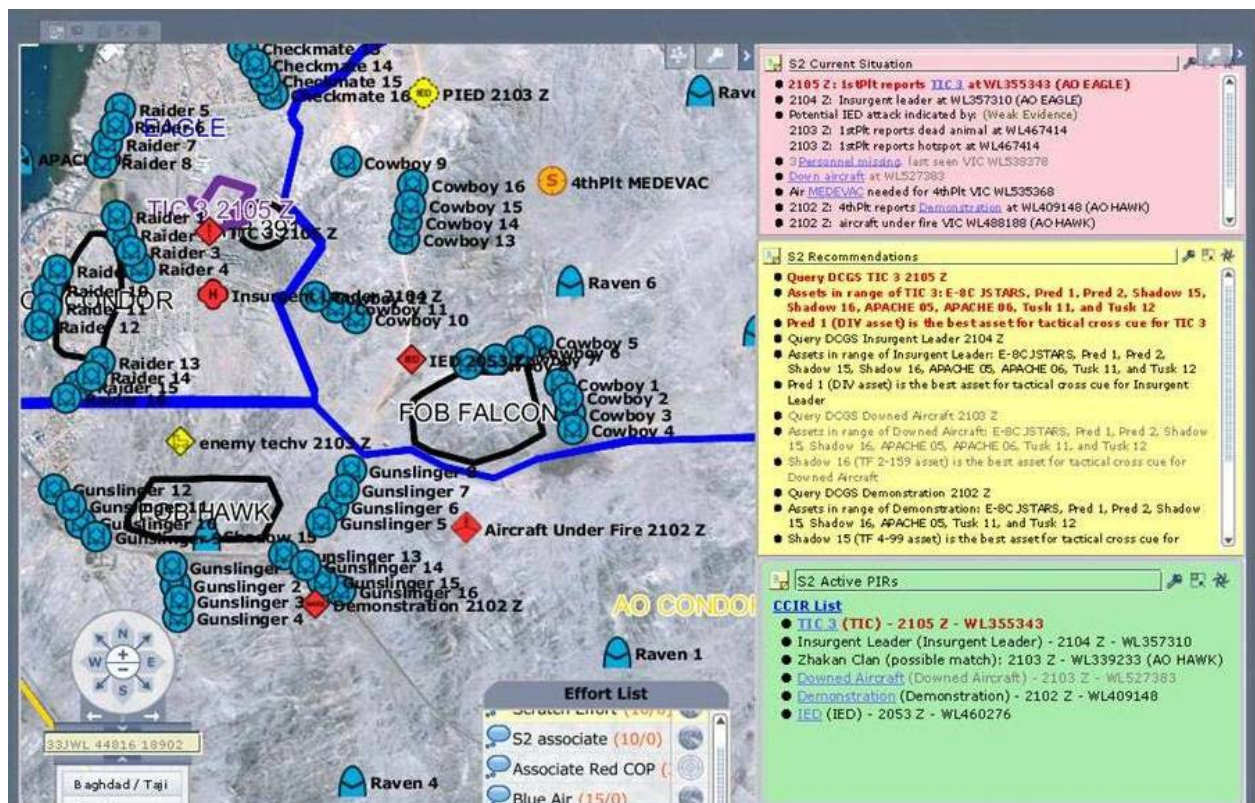
Figure 5. WA screenshot for the Operations Officer (S2) as implemented on the CPOF–Army Mission Command System.
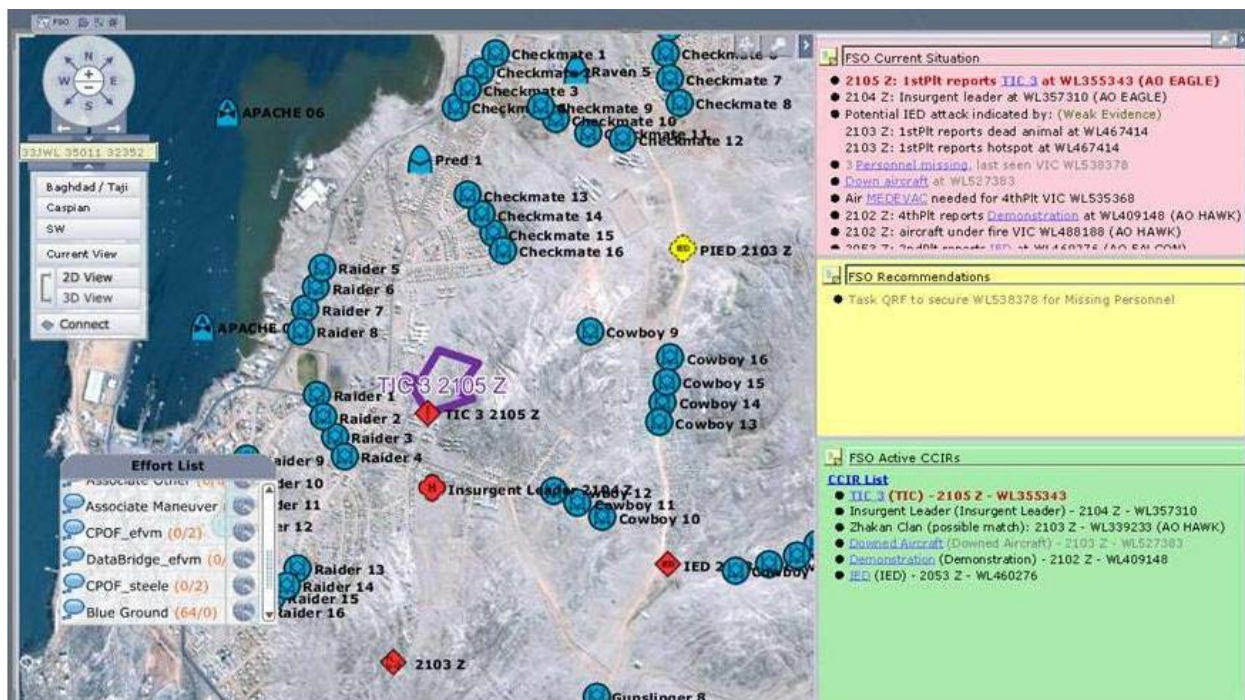
Figure 6. WA screenshot for the Operations Officer (FSO) as implemented on the CPOF–Army Mission Command System.

5.2.3 Decide (Action Selection)

The *decide* phase of the decision-making cycle is focused on selecting an appropriate course of action given an assessment of the situation. It is perhaps the most difficult to address as it is heavily dependent upon robust knowledge engineering to construct a knowledge representation that understands different role-positions and hierarchical goal configurations in response to various situations and the plans or means to achieve them. Fortunately, the military domain has a corpus of doctrinal knowledge that serves as a template for guiding appropriate decisions. Continuing with our vignette, in response to the HVT reported in the AO, a number of plan proposals are triggered for the S2 intelligence officer to identify ISR assets that may have captured the event as well as identifying assets that may be able to provide the best focused coverage. Next, the plans and goals to perform mission tailored surveillance are instantiated by the firing of two plan proposals for the S2: <Use Most Appropriate Equipment for Tactical Cross Cue> and <Use Equipment in Area for Tactical Cross Cue>. In this specific case, the WA knows that there are surveillance assets overhead from the unit and asset position information available on the Army Battle Command System. One of the intelligence officer's (S2) goals is to have adequate surveillance. If there are no surveillance assets within range, the WA will send a message to the S2 recommendation dashboard in CPOF to coordinate surveillance. Note that this recommendation is triggered at a later time (9:08) in our vignette—in response to troops in contact; in this case, the notification <No ISR Asset Covering Threat> is activated for the S2. The WA uses an algorithm to compile eight different variables and based on match scores,

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specifies the best available assets for tactical cross cue. The S2 recommendation dash board (yellow box) lists all available ISR assets and the best available. For a sample screenshot of the S2 recommendations provided by the WA (S2 instance), see figure 5.

5.2.4 Action (Action Implementation)

The *action* phase of the decision-making cycle is focused on action-implementation and plan execution. As currently implemented, the WA strictly maintains a human-in-the-loop stance. Plan recommendations are pushed to the user in the *decide* phase, but are left to the user to act upon. There are a few actions, however, that the WA will undertake on behalf of the user that are more-or-less geared toward low-level network information management.[*] The intelligence officer (S2) is also tasked with analyzing and synthesizing available information. In our HVT example, this prompts the goal and plan proposal <Provide Context> in our vignette. The ensuing action <Query Database for Events> is triggered for the intelligence officer (S2). In this case, the WA will query intelligence repositories on the Army Battle Command System, such as the Distributed Common Ground System – Army (DCGS-A) for information related to the HVT in the context of the broader tactical and strategic situation and provide support accordingly. For instance, highly-relevant information may be returned such as previous sightings, known modes of transportation, etc. Another triggered action includes <Issue SPOT Report> for the operations officer (S3). This action by the WA automatically produces a standard information template about the reported HVT event to be relayed up the chain of command for the operations officer. In the action phase, the goal of the associate is to facilitate action and assist with information management tasks that associates are well suited for.

The action <View Area> is also triggered for all three associates in our vignette. This action is a placeholder to enable future technological development in handheld and wearable battlefield computers. Once <View Area> is triggered, the map can be pan-and-zoomed to the HVT sighting for a patrol in the area. When an event has been resolved, the icon and C2 pointer will be removed from the map display in CPOF and the notifications will be grayed out.

5.3   Current Extent of Our Knowledge Engineering Effort

Thus far, we have stepped through just the first reported incident of many that occur in our AO during an arbitrary time period. As currently developed, the WA is able to respond to:

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[*]These were carefully selected to adhere to the Associate System principle of decision-support and avoid developing an overtly proscriptive system that would interfere with and thus quickly be rejected by the user. For the action phase, we selected obvious low-level actions that could be easily performed by computers and are more onerous for humans.

- All normal doctrinal operations

- Troops in Contact

- Personnel recovery/downed aircraft

- MEDEVAC and casualty evacuation

- IEDs, including vehicle-borne IEDs, suicide-vest IEDs, and potential IEDs (P-IED)

- Indirect fires (e.g., mortar attack) with point-of-origin (POO) and point-of-impact (POI)

- Deconflicting airspace

- HVTs

- ISR asset management

- Unit boundary coordination

- Joint and coalition coordination

- Minefields

- Civilian demonstrations

- Air threats

Our vignette covers a range of these events, such as: TIC, demonstration (riot), P-IED, IED, POO, MEDEVAC, IED, and air threat. How the WA supports the S3-S2-FSO during their decision-making cycle is fully described in table 1. The decision-making cycles are generally triggered in much the same manner with notifications of an active threat in the AO. Note the important subtleties during the subsequent phases that vary according to the event, role-position (S3-S2-FSO), positioned assets, and other ongoing events. For example, during the mortar attack (21:39), the plan proposals for ISR tactical cross cueing are shared between the S2-FSO in order to instantiate support for a counter-strike battle drill. In some cases, ISR assets are positioned over the event and at other times the S3 needs to coordinate ISR management. Finally, the WA is able to cross reference battlefield events, such as when the HVT is spotted at grid locations next to an ongoing demonstration (28:48).

The WA provides a dynamic real-time model of human intention and provides mission command with the ability to engage in high up-tempo operations with support for planning and plan execution and fault tolerance. It fosters rich human-computer collaboration and addresses the complexity of mission command in a network-enabled operational environment.

6. Metrics for Mission Command

6.1 Activation Dynamics of Warfighter Workflows

The authors of the research team realized that the WA can provide novel metrics for assessing human performance in a mission command environment. The fundamental insight is that the underlying activation of the knowledge structures in the WA can provide a dynamic *real-time* model of human intention that has the potential to support the analytical community with novel classes of metrics. This is no small feat as it addresses a long-standing, difficult problem, that of objectively measuring mission command effectiveness at the individual and team level.[*] These metrics can be derived from the pattern of node activations from the knowledge-base (O-O and D-A graphs) and used to gauge the effectiveness of the mission command staff. The training community would benefit greatly from automated metrics for scenario-based exercises as well as state-trace detailing staff performance across the decision-cycles and also the occurrence and timing of important points of staff collaboration.

6.2 Capturing and Analyzing Mission Command Performance: Metrics Overview

In this section we highlight some metrics from the underlying pattern of node activations. These metrics are important as a research topic because these issues have important design implications for current and future networked mission command systems. Without consensus on the measurement of these issues, design teams and system managers have little guidance on system performance weaknesses until the system is fielded. The WA provides useful metrics of performance rooted in an analysis of the workflow (activation of goals and plans in the D-A graph and concepts in the O-O graph):

- Cognitive workload (number of concurrently active goal and plan nodes in the D-A graph across time)

- View graph of currently active knowledge

- Automated timing measures of task completion (time from goal activation to closure)

- Highlight collaborations (users that have shared active goal nodes at a given time)

- Force synchronization (time to collaboratively close-out shared active goal nodes)

Since the knowledge includes a dynamic model of the operational environment, and the user interface is updated with appropriate alerts, suggestions, and highlighting of critical information as time progresses; the knowledge representations serve as *state traces*. The state traces depict

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[*]This hard problem was the recent (January 2012) focus of a workshop by the Military Operational Research Society entitled "Joint Framework for Measuring C2 Effectiveness" held at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD.

the cognitive work demands on the mission command staff across scenario runtimes as dynamic events unfold. A suite of data analysis tools (DAT) was developed to look at the underlying node activations in the knowledge structures, which include an instance viewer, a log analyzer, and a shared event analyzer.

6.3   Data Analysis Toolset

The DAT has four primary components that are used to view node activations and a log output of moment-by-moment changes in activation states, which will be described in detail in the subsequent sub-sections:

- Instance Viewer: Active nodes in the knowledge structure, which provides a heat map for cognitive work analysis.

- Cognitive Workload Chart: Time series figure of activation and deactivation of nodes, which shows cognitive workload.

- Log Analyzer and Task Completion Timing: The start and stop times for events, e.g., IED, TIC. Events include input data, alerts, recommended COAs, and actual COAs and are anything that triggers node activations and deactivations in the knowledge structures.

- Shared Event Analyzer: Events can be shared across roles, requiring collaboration. For example, an air MEDEVAC requires coordination between the FSO, S2, and S3. The Shared Event Analyzer measures collaboration (team performance) and force synchronization.

A concise database schema depicting system monitoring, events, nodes and their relationships is provided in the appendix, "Data Analysis Toolset: SQL Database Schema."

6.3.1 The Instance Viewer

6.3.1.1 Cognitive Work Analysis Heat Map

The instance viewer shows currently active nodes in the unified D-A Graph and O-O Graph for each running instance of the WA. The instance viewer has two functions. As shown in figure 7, the *heat map* function allows one to view either current "real-time" work activity (active nodes) in the D-A and O-O or alternatively, summed-up over a specified epoch of time. Often, repeated goals, plans, and concepts will have the highest activation and are depicted by the warmest colors. This snapshot of the work domain is useful in understanding and summarizing work activity as a constellation of activated goals and plans to achieve them and provides a detailed accounting of cognitive work activity across time. For example, this tool could distinguish between two individuals, one who stuck closely to an established and carefully prescribed work flow and another who worked dynamically and broadly across many different domain areas (i.e., multi-tasking).
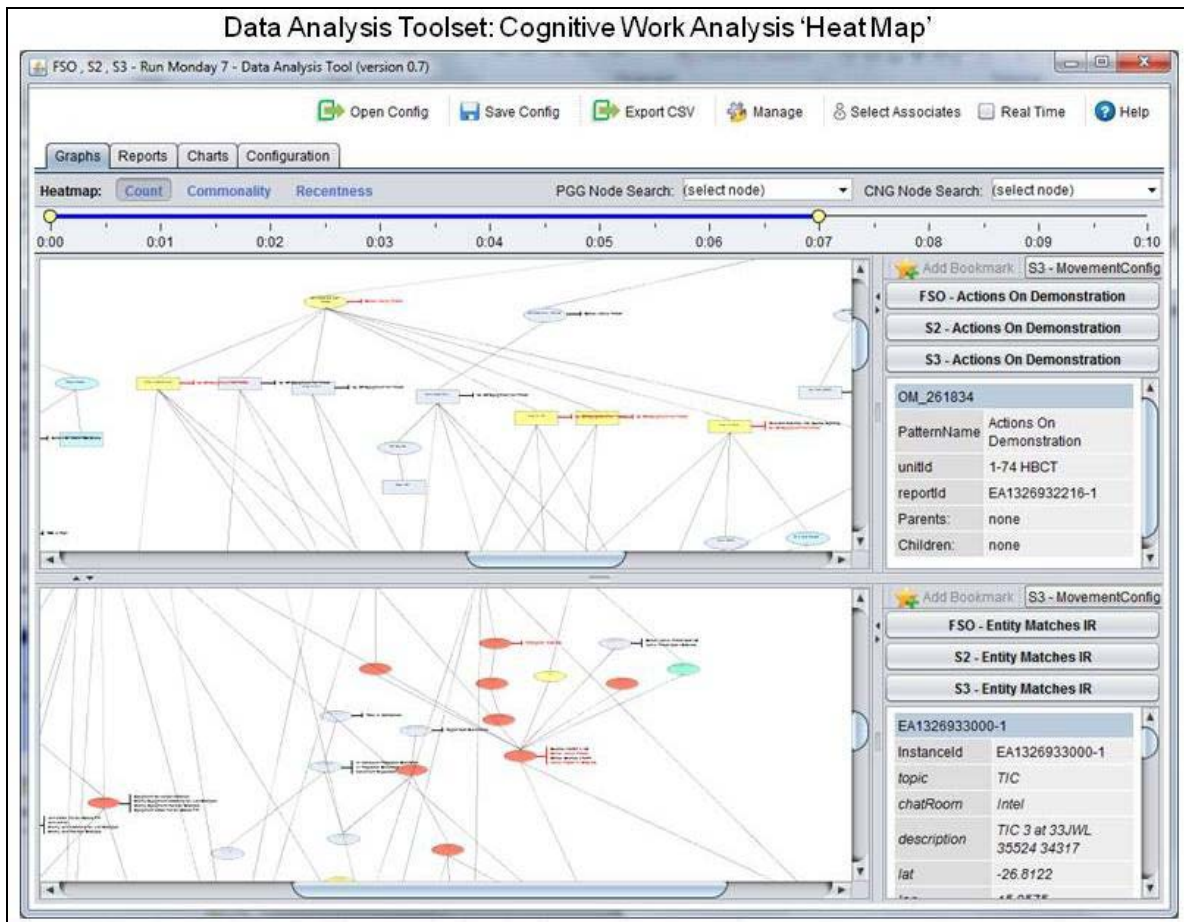
Figure 7. Cognitive work analysis "heat map" of D-A graph (top) and O-O graph (bottom) activations as the number of times each node was triggered across specified time period, here the first seven minutes of the scenario data run as specified by the onset and offset bubbles of the blue time slider bar. This tool can also be used to observe currently activated nodes if the "real-time" box is checked in the top right. Warmer colors depict greater node activation counts; this is user configurable where numerical ranges can be specified and assigned to any selected color scheme.

The current standard in the field of cognitive modeling[*] is to develop and run computational models of cognitive tasks as a simulation and then, to compare the simulated data to human performance data using goodness-of-fit statistics. There is a real need for descriptive and analytical models of how cognitive work is accomplished with both the attendant real-world complexity and the collaborative dimension of group decision making. Our approach is to

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[*] ACT-R modeling (Anderson and Lebiere, 1998) is currently a gold-standard in computational modeling that can account for human cognitive performance across a wide-range of domains, from perception and attention to learning and memory phenomenology to complex problem-solving. The ultimate goal of cognitive modeling, however, is to develop a unified theory of human cognition by developing comprehensive computational models successively held to account for an ever-increasing range of human information processing capabilities (Newell, 1990). This goal differs from our current approach in a profound way. Our approach is analytical and encompassing, to offer new metrics to capture and analyze human cognition, group collaborative processes, and naturalistic decision-making (see Klein, et al., 1993) as it is manifest in the information-rich and complex networked environment of Mission Command.

model a cognitive work analysis of the goals and the plans to achieve them in *real-time* as the work dynamically unfolds as a complex network of tasks. A new capability of an analyst to record and view work activity dynamically and unobtrusively over specified epochs of time is, to our knowledge, unprecedented.

6.3.1.2 Cognitive Workload Chart

Cognitive workload is the amount of demand on limited cognitive resources required to accomplish mission requirements for a human operator. The recognition of cognitive workload as an important aspect of behavior emerged from studies of work performance and subjective assessments of job demands (Wickens and Hollands, 2000; Wierwille and Eggemeier, 1993). Increasing job stress or performance pressure results in performance improvement up to a point. After that, increased job demands sharply reduce performance. This parabolic workload-performance curve has been widely established and is known as the Yerkes−Dodson relationship (Yerkes and Dodson, 1908). Importantly, it defines a zone of maximal performance. Cognitive workload fluctuates over time; in practice, this means that cognitive workload is a time series that needs to be averaged over defined time periods that are short enough to allow detections of low, optimal, and peak workload states. The goal of managing Soldier-system interactions is to keep performance over time within the optimal region of performance. Note however, that performance is variable within an individual and over time. The optimal region might fluctuate due to a host of intra-individual factors, such as: fatigue, multitasking demand, stress, reduced attention span, etc. Nevertheless, being able to objectively measure cognitive workload as a time series has practical utility in better aligning and achieving maximal Soldier-system performance, as well as better understanding intra-individual sources of variability.

There are, however, no reliable, unobtrusive, direct measurements of cognitive workload. The current standard of measuring cognitive workload is the NASA Task Load Index (see Hart, 2006), which is a subjective survey method whose administration requires that one stop the field exercise or experiment. Recent direct measurements of brain activity suggest a path forward, but these methods are in the research stage and not fully mature technologies (see Dornhege et al., 2007). Thus, currently unobtrusive measurement of cognitive workload cannot be performed under realistic operating conditions.

Our formal metric construction of cognitive workload is derived from the activation of the user workflows in the D-A graph that is triggered from directly observable behaviors. Our measurement approach provides an *objective* and *time series* measure of cognitive workload that is also defined by meaningful Mission Command behaviors. In figure 8, we provide a screenshot example of the instance viewer. In this case, the goal node <Each Threat Managed> has been selected and the dynamics of node activation and deactivation (satisfaction) are shown across time. Note that here the count step-size is by three because all three instances of the WA—the S3, S2, and FSO—have been selected in the dataset and this node is similarly triggered and

deactivated across all three instances. These graphs can also be shown independently for each running instance of the WA

The instance viewer shows the number of concurrently active O-O and D-A nodes that are active either at a given point in time or across a specified time frame for a select node. This offers a useful measure of cognitive workload as given by the staff task demands at any point in time. In our case, we define cognitive workload as the number of concurrently active goals and sub-goals to achieve them. A limitation of the current approach is that not all goals are equally complex. Following the approach of Bierbaum et al. (1989)—who developed a workload prediction model for piloting a UH-60 helicopter—it should be possible to derive estimates of the workload demands associated with each goal node in the D-A graph; thus assigning to each goal a level of difficulty that can be aggregated into a composite measure of cognitive workload.
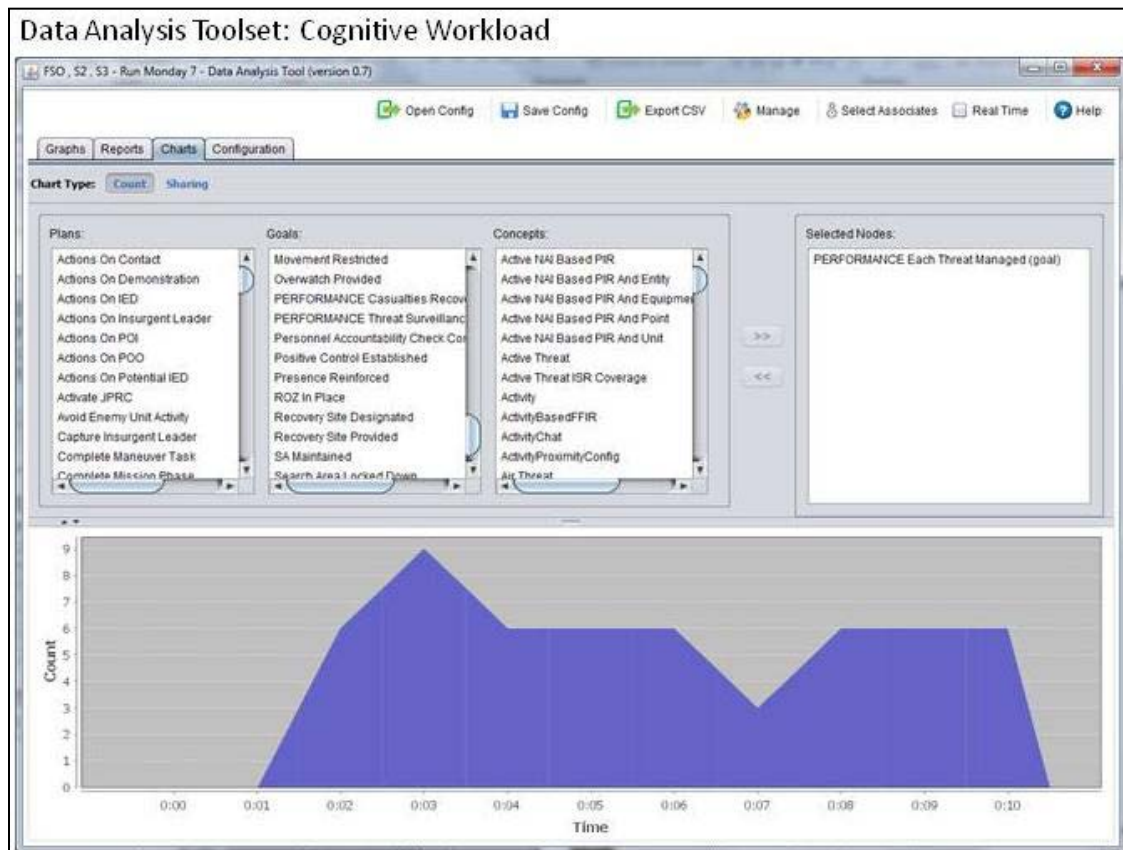
Figure 8. The activation of a specified plan, goal, or concept node can be observed across any period of the experimental scenario run.

Our metric is important as it offers an objective and continuous measure of cognitive workload that can be collected unobtrusively. It also has the advantage of being part of a system designed to provide decision support. Node activations could provide an unobtrusive and continuous metric of cognitive workload that could then be fed into mission command systems as an

estimate of user workload. System configurations (interface) and capabilities (alerts) could respond to this continuous estimate of user cognitive workload to achieve optimal Soldier-system performance.

6.3.2 Log Analyzer: Data Capture and Behavioral Analysis

In scenario-driven military experiments/training-events, it can be challenging to precisely recreate and playback what happened during runtime, even with a solid data collection and analysis plan. For instance, it is difficult to establish the timeline of whether and when events occurred in a scenario-driven military training event, especially when unplanned interventions and schedule delays are introduced during execution time. Precisely capturing the timing of events and information flows is critical to enabling the military analytical community to advance a scientific capability to understand and address the challenges and complexities inherent in network-enabled mission command.

The Log Analyzer addresses these challenges by capturing D-A graph instance start and stop times, monitor events, and notification events for each running instance of the WA. This is essential for defining performance. The Log Analyzer is shown in figure 9. With this tool the analyst can search the log files generated by the WA system to better understand Soldier and system performance. The log files can be filtered and sorted on several dimensions (see figure 9, right panel) to include: associate, start time, update/stop time, duration, name, attributes, type, and lifecycle state.

Based on the Log Analyzer, key performance metrics include: operational tempo, resource management, and information flows. Performance can be defined in terms of operational tempo (task completion time), efficiency of resource allocation, tracking when battlefield events actually occurred during scenario runtime and when and what recommendations were given to the users. Operational tempo refers to how quickly the staff is able to cycle through decision making in effecting the battlefield. The Log Analyzer provides task completion timing, the onset and duration (to goal satisfaction) of critical battlefield events. Resource management refers to how well the staff is able to coordinate and prioritize the use of limited battlefield resources. This is especially the case with ISR assets. The WA monitors the location and status of all assets in the battle space and pushes recommendations; and all of this data is captured in log files and a database. Using the Log Analyzer, an analyst can determine whether and when assets were tasked to assess efficiencies. Finally, the Log Analyzer gives access to the full timeline of information as it is reported or pushed on the network (i.e., chatroom or voice communication transcribed to text) by the Soldiers and the WA system. This is essential for capturing and analyzing the complex information flows that occur in the Mission Command network.
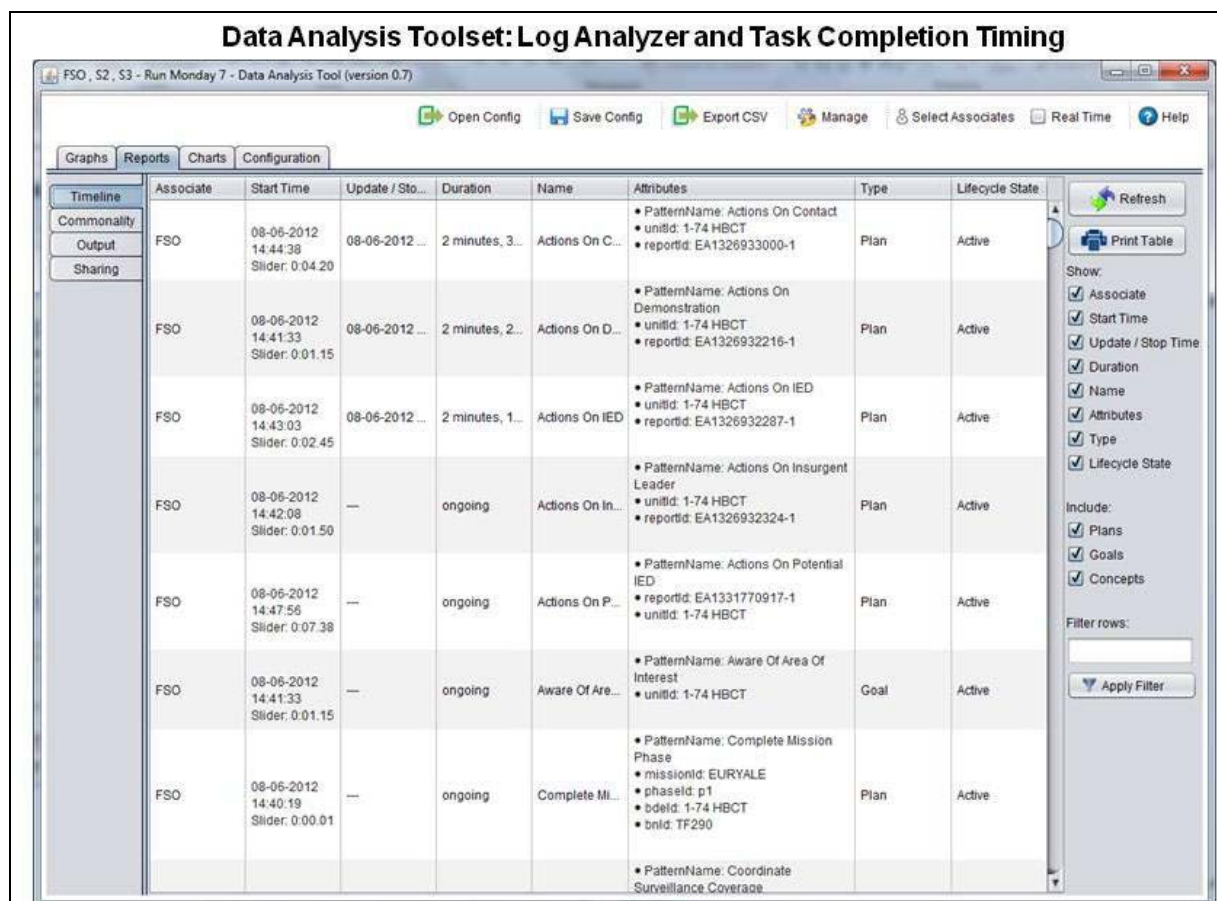
Figure 9. The log analyzer catalogs the D-A graph instance start and stop times, monitor events, and notification events for each running instance of the WA. The log files generated by the system can be filtered (right panel) in order to better understand Soldier-system performance and extract metrics of task completion timing, such as the onset and duration of critical battlefield events, resource allocation, and the timeline of information pushed by the Soldiers and the Associate System.

6.3.3 Shared Event Analyzer

A shared event is defined as activated O-O and D-A nodes that are shared by multiple WA Instances, in our case by any combination of the S2 (Intelligence Officer), S3 (Operations Officer), and FSO (Fire Support Officer). The Shared Event Analyzer captures the time and content of each shared D-A and O-O node instance and displays a representation of the shared events between multiple WA Instances. This is illustrated in figure 10 whereby the color of the D-A nodes (for the MEDEVAC hierarchical sub-tree) denotes unique or shared responsibilities. In this example, task responsibilities that are shared by all three role positions (S3, S2, FSO) are shown in grey, whereas those shared by the S3 and FSO in orange, and those unique to the S3 or FSO are in green and yellow, respectively. Two metrics can be derived from such a representation: collaborative information flows and force synchronization.
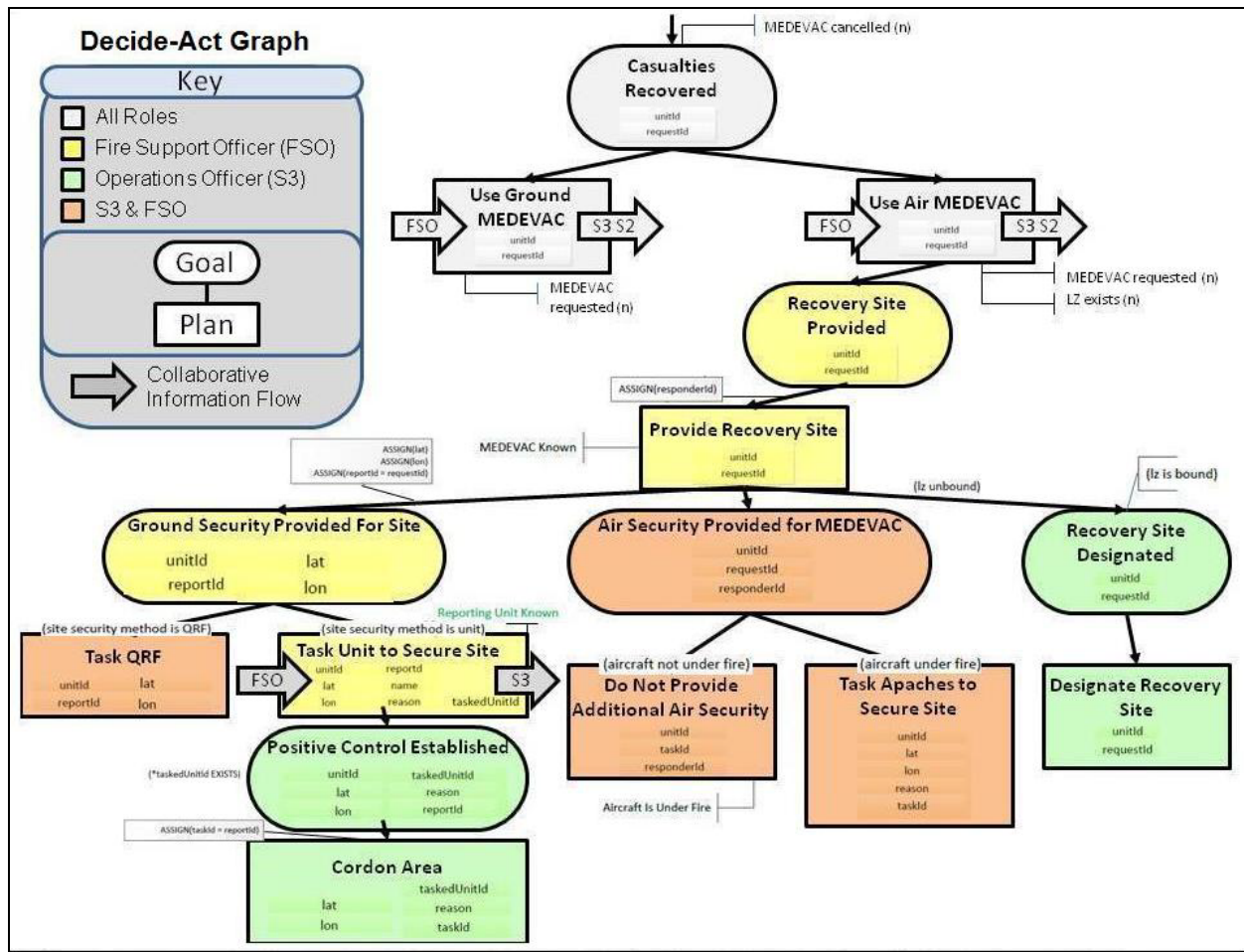
Figure 10. Illustrated sub-section of D-A graph hierarchy for MEDEVAC operations.

6.3.3.1 Collaborative Information Flows

Most tasks are not planned or executed in isolation, either in terms of other tasks or in terms of other actors and stakeholders. The essence of teamwork is the ability to efficiently maintain a coherent set of tasks across many actors and assets in a manner that does not conflict with one another. Geddes (1994) provides an analysis of conflicts across multiple actors and assets to identify two separate families of conflict: Goal Conflicts and Plan (or activity) Conflicts. Recognizing that both goals and activities are hierarchical in nature, this analysis explicitly addresses sub-goals and sub-activities and the differences between purposeful state changes (goals) and incidental state changes ("side effects") at different levels of activity aggregation and decomposition. As noted by Geddes, two plans that may seem perfectly compatible at one level of aggregation may have serious side effect conflicts at a lower level of decomposition that blocks their successful joint execution across the team. Geddes also makes the case that only some of the conflicts can be detected and avoided at "design time." From a systems engineering and behavioral research perspective, there is always a fundamental need for "execution time" conflict detection and correction across teams (Geddes, 2011). Our method of tagging

collaborative information flows and the metric of *force synchronization* are tools that the analyst can use to assess teamwork during execution time.

The method of tagging collaborative information flows on the D-A graph (as input and output arrows) allows one to determine whether these staff processes were mutually supported during task execution. A sub-section of the D-A graph is illustrated in figure 10. In this illustrated sub-section, the plan [Use Air MEDEVAC] is tagged with arrows where necessary collaborative information flows are represented. The FSO is responsible for responding to an air MEDEVAC request. The WA reads the MEDEVAC request from the chat room input and then prompts the FSO by posting this request on their graphical user interface, the "FSO Current Situation" CPOF stickie (refer to figure 6). The arrow to the right of the [Use Air MEDEVAC] plan indicates that the WA shares this information with both the S3 and S2. The operations officer, S3, is responsible for all force protection activities of Soldiers and civilians in location of the designated MEDEVAC site. And if the MEDEVAC was induced by enemy activity, then it is important that the intelligence officer, the S2, provide actionable intelligence to the MEDEVAC crew on the enemy disposition in the area.

The illustrated sub-tree details mission concepts and staff workflows, such as designating and providing ground security for the recovery site as well as air security for the MEDEVAC. In satisfying the sub-goal <Ground Security Provided for Site> the plan [Task Unit to Secure Site] is activated if a unit is tasked to provide site security. The arrows indicate a necessary collaboration between the FSO managing the MEDEVAC request and the S3, responsible for establishing positive control over the designated recovery site by cordoning off the area. In tagging the D-A graph with collaborative information flows, the WA actively supports collaboration. The analyst uses the Log Analyzer toolset to determine whether mission concepts and staff workflows were indeed supported.

6.3.3.2 Force Synchronization

The metric of *force synchronization* attempts to measure collaborators' coordination of shared activities and purpose across time and space. The concept of *force synchronization* applies to groups of actors that desire to arrive at a set of goal states by achieving a set of intermediate states in a specific sequence (Geddes, 2011). While the sequence of intermediate states is often described in terms of time and space, force synchronization can also refer to the synchronization of staff workflows along the social and cognitive dimensions. For example, in the case of Soldier-information systems, synchronization may involve communication and decision sequences with accompanying states of data and awareness. Synchronization exists by degree. Perfect synchronization can be said to exist when all of the actors achieve each of the intermediate states they are responsible for according to the expectations of the other actors and in a manner that does not create a conflict, either direct or indirect, between the actors (Geddes, 2011). And, synchronization is an integrative measure that occurs over a period of time rather than at an instant. As a result, there is a characteristic time period over which synchronization

can be measured. The time period chosen for measurement should be long enough to capture the full time series of shared activity.

Our metric definition of force synchronization is based on the timely co-activation of essential tagged D-A nodes by collaborators in response to shared significant events (e.g., battle drills) across a period of time. For instance, the timely response and satisfaction of an air MEDEVAC request requires that the staff quickly work through several collaborative sequences in tandem to satisfy several intermediate goal states, from designating and tasking units to secure the recovery site (S3), to establishing an air corridor and air security (FSO), to providing intelligence on enemy force disposition in the immediate vicinity and threats along the air corridor (S2). A staff with a high-degree of force synchronization can achieve their intermediate goal states in a timely manner that does not create conflict with one another. The Data Analysis Toolset allows the analyst to view the activation dynamics of the D-A graph and possibly identify friction points of collaboration that contributed to poor force synchronization, or simply assumptions and workflows that were overlooked. For instance, perhaps an inordinate amount of time was spent satisfying the goal <Air Security Provided for MEDEVAC>, or alternatively, perhaps the goal was not attended to, nor satisfied. The analyst would then be clued in to determine why that was indeed the case. Possible factors influencing force synchronization include the quality of task execution, situation awareness, shared understanding, and team collaboration. Continuing our example, perhaps the staff had an incomplete picture of enemy air threats and thus spent a considerable amount of time seeking information and then deliberating whether to request additional air security assets (e.g., Apache helicopters). Or alternatively, perhaps the staff did not challenge their assumptions and implicitly assumed the mental frame of no known enemy air threats. In sum, the activation dynamics of the D-A nodes provide the analyst with a state-trace of the collaborative workflows underlying our proposed metric of force synchronization and important markers to uncover the governing dynamics of staff collaboration.

6.4 The Big Picture: Assessing Mission Command Staff Performance

For the analyst, the utility of new metrics are determined by how well they capture meaningful staff performance. This depends on how well the system represents activated domain knowledge over the course of execution time. This section provides a concrete example of the utility of our metric approach. The Data Analysis Toolset captures and assesses cognitive workload and Mission Command performance. In figure 11, the activation counts of several goal nodes from the D-A graphs are depicted across scenario runtime (for cross reference, see table 1). A high-level goal node <Each Threat Managed> can track current threats in the AO. As a metric, the activation profile of this high-level goal node represents the many different workflows of responding to threats. In our vignette example, the activation count increases steadily as more and more compounding events occur in the AO. In representing the number of active workflows, the <Each Threat Managed> goal node is perhaps a good candidate for our measure of cognitive workload for the entire staff. Note that the step size is 3, representing each instance of the WA: S3, S2, and FSO. Other goal nodes shown in figure 11 may capture cognitive

workload for more prescribed workflows for particular staff responsibilities. For instance, the goal <Ground Security Provided for Site> reflects S3 responsibilities for ground security; the goal <Context Provided> reflects S2 responsibilities for querying an intelligence database; and the goal <Thread Surveillance Adequate> reflects instances that require the management and potential re-tasking of ISR resources.
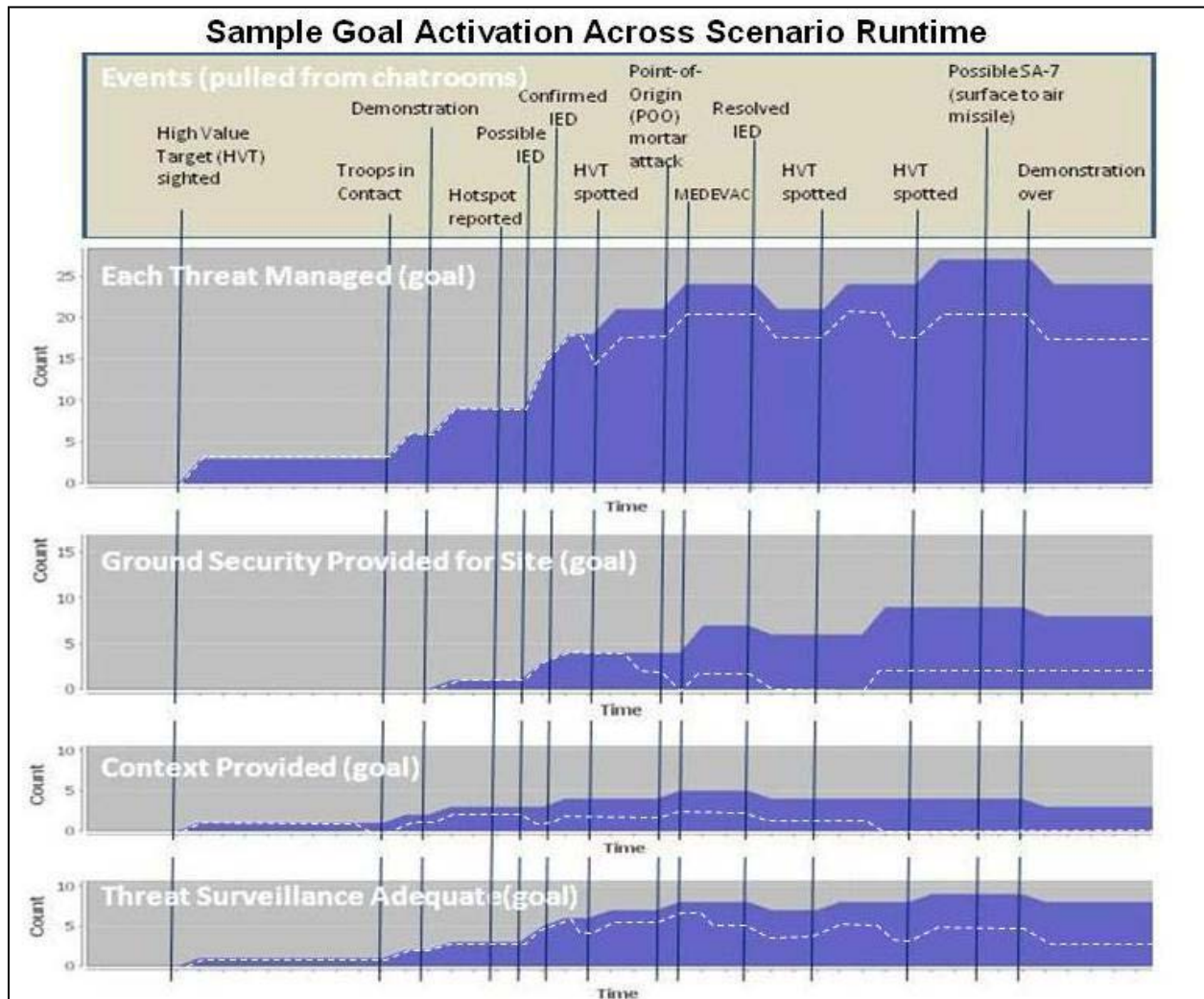
Figure 11. The activation of several goals from the D-A graph across the vignette scenario runtime (see table 1). The goal <Each Threat Managed> is perhaps a good proxy for staff cognitive workload, whereas other goals pertain to more prescribed responsibilities. The goal <Ground Security Provided for Site> pertains to the Operations Officer (S3) duties, whereas the goals <Context Provided> and <Threat Surveillance Adequate> are Intelligence Officer (S2) responsibilities for querying the intelligence database and managing ISR assets, respectively. The filled in area represents the baseline condition of goal activation with no staff involvement, whereas the dotted line is the experimental condition depicting a runtime trace of goal activation/satisfaction with staff involvement.

The time course of goal activation can also be rendered against a standard baseline of comparison. The dotted lines in figure 11 reflect the time course of how well the staff responds to events in the AO. To arrive at this graph, the scenario is run in a baseline condition—a *dry run* without staff involvement— represented by the filled in area. The experimental condition is then run with staff involvement given by the dotted line in each of the graphs in figure 11. This difference is a measure of what has been termed *manifest agility* by the Command and Control (C2) operational research community (Alberts, 2010). According to Alberts and Tillman (2012), manifest agility is defined by the response to an event that has occurred and this involves comparing what actually happened to what would have happened if no change had taken place. Thus, the activation dynamics depicted in figure 11 reflect the manifest agility of the entire staff and in effecting overlapping work responsibilities.

As an aside, this approach can also be used to assess the effectiveness of any prototype technology. In this case the experimental design requires two conditions, one with and another without the prototype technology. Used in this way, the WA would simply run in the background and not contribute decision-support. Instead, the WA would provide the metrics framework for assessing staff performance with and without the prototype technology. For the acquisition community, these metrics could provide solid benchmarks of performance to assess the effectiveness of any prototype technologies, such as a new MCS or a MCS implemented on mobile devices, across the development cycle on a range of dimensional metric parameters.

Another important future direction for this research is to validate these measures of cognitive workload and force synchronization in laboratory experiments. The cognitive workload measure, for instance, could be compared to standard subjective measures, such as the point estimates of the NASA Task Load Index (Hart, 2006), as well as more direct measurements of brain activity. In the latter case, electroencephalography can be used to record and render a time series of electrical activity along the scalp. It would be very interesting to examine whether there exists a robust neural signature associated with the time course of goal activation, as inferred from the state traces of the WA.

7. Enabling Operational Agility

In 1986, the U.S. Army adopted a definition of agility as one of four tenets of operations in its maneuver-oriented Air Land Battle doctrine which still stands today (FM 100-5 Operations, 1986). More recently, agility has been defined in terms of Boyd's theory of maneuver:

Agility is the ability of friendly forces to react faster than the enemy… It is as much a mental as a physical quality. Greater quickness permits the rapid concentration of friendly strength against enemy vulnerabilities. Forces may need to concentrate repeatedly so that by the time the enemy reacts to an action, another has taken place, disrupting the enemy's plans and leading to late, uncoordinated, and piecemeal response. This process of successive concentration against locally weaker or unprepared enemy forces enables smaller forces to disorient, fragment, and eventually defeat much larger opposing formations. (Lind, 1993; cited in Polk, 1999)

As noted by Polk, this definition of agility fits squarely within Boyd's theory of how one could operate inside the adversary's OODA loop to get inside the enemy's Mind-Time-Space and underscores the extent of John Boyd's influence on modern Army operational thought. In its purest form, the OODA loop is a theory of operations with the central tenet of operating at a faster tempo to "get inside the OODA time cycle or loop" of an adversary.

At the staff level, the WA enables agility by enabling the Mission Command staff to cycle through the OODA loop quickly, with the goal of reacting faster than the enemy. The knowledge representation of the WA system is a key enabling technology. It also directly addresses the data-to-decisions hard problem of providing the right information to the right Soldier at the right time. Without a model of Soldier workflows it is impossible to provide tailored decision-support.

From an organizational perspective, the WA also enables operational agility. As noted by Polk, the generation and management of tempo are critical in large, complex organizations; and this is perhaps especially the case in complex Mission Command network-enabled environment:

An organization risks failure by inappropriately responding at every level to the competing and often overlapping OODA phases. In response, Boyd counsels that the time needed to complete an OODA cycle increases with each ascending level in the decision-making hierarchy as the number of events one must consider correspondingly increases. Consequently, subordinate levels must harmonize their work within the higher's slower rhythm and larger pattern to maintain consistency in the system. Higher, in turn, must give lower commanders wide freedom, within the overall Mind-Time-Space scheme to shape and direct their own activities so that they can exploit faster tempo/rhythm at tactical levels… (Polk, 1999, p. 15)

That is, intelligent agent systems such as the WA can speed up the slower rhythm of higher command echelons and allow a faster operational tempo and agility in responding to lower echelon's needs and the fast pace of the tactical edge.

Agility is related to the Army's information-age transformation to network-enabled operations. It is commonly accepted that a robustly networked force is more agile by virtue of being increasingly connected (Atkinson and Moffat, 2007). However, this is not necessarily the case. One of the growing pains in the shift to network-enabled operations is the recognition of the human cognitive capacity and processing speed limits. There is a need for intelligent software that can do what computers are good at, rapid processing and searching of large amounts of data, and to aggregate and summarize relevant information for the human decision-maker. The corollary is that the human operator needs to be freed from burdensome information management and configuring displays to fully exercise the art of command and engage in collaborative critical thinking, decision making, sense making, and reasoning.

The WA provides capabilities to both improve and evaluate performance in Mission Command, including difficult to quantify concepts such as operational agility. Another potential application of the WA is training technology. The alerts and decision aids offers Soldiers' support in Mission Command and performance can also be evaluated and used during debriefings in after-action reviews. The WA could reduce training time, and thus training costs, while increasing Mission Command performance through situated practice in scenario-based training and in the application of doctrinal knowledge. In terms of practical utility, the WA also potentially addresses organizational and environmental challenges in providing decision-aiding to Soldiers whom are inexperienced, fatigued, or both.

In sum, the WA addresses a major tenet of the U.S. Office of Secretary of Defense's "data to decisions" initiative and the primary challenge for military commanders and their staff to shorten the cycle time from data gathering to decisions. In supporting the full sequence of "data to decisions," the WA system ensures that it occurs in a timely and accurate manner, and provides a novel class of metrics to assess the operational efficiency of Mission Command.

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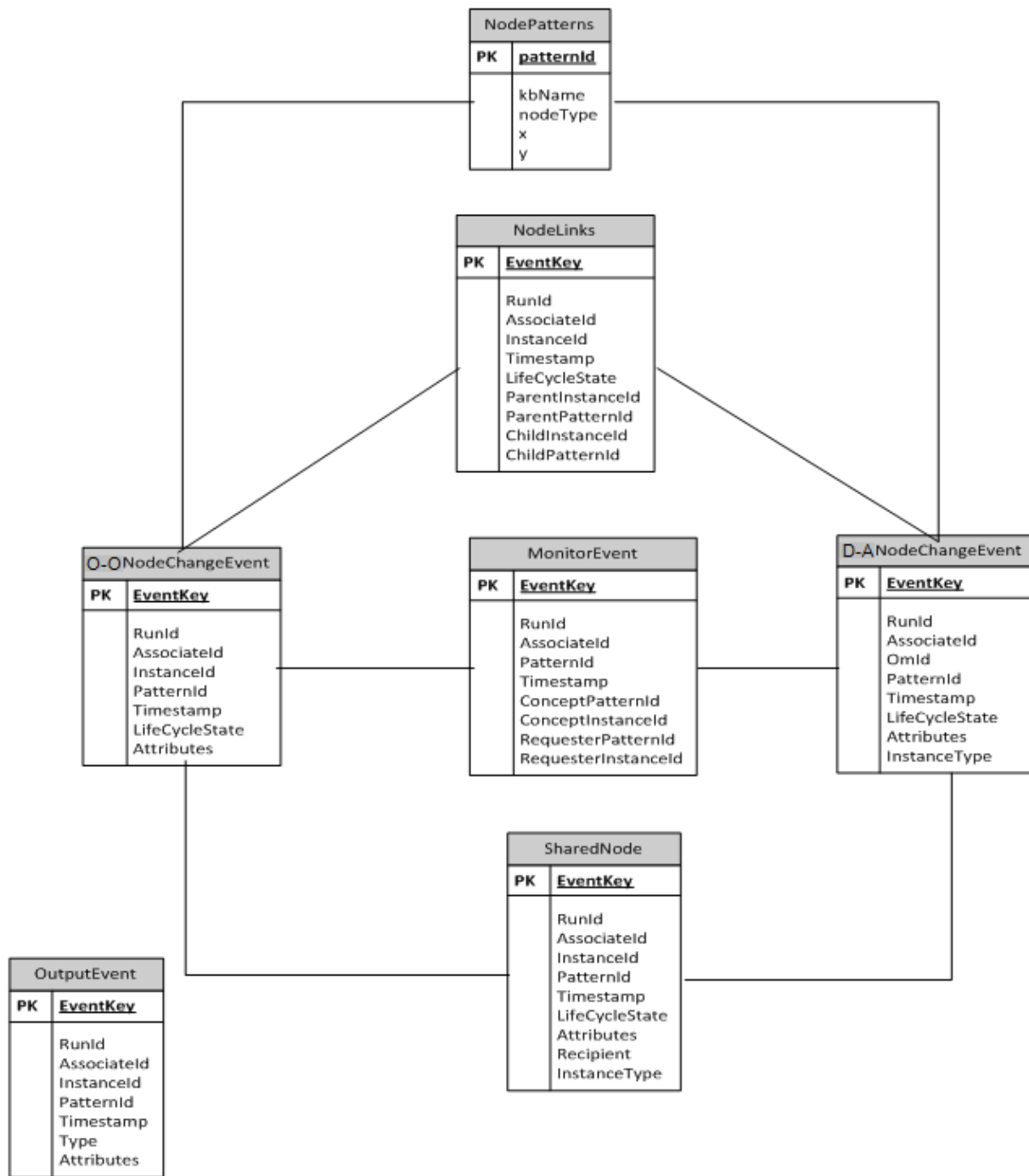
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Appendix. Data Analysis Toolset: SQL Database Schema

This appendix appears in its original form, without editorial change.

NodePatterns

PK	patternId
	kbName
	nodeType
	x
	y

NodeLinks

PK	EventKey
	RunId
	AssociateId
	InstanceId
	Timestamp
	LifeCycleState
	ParentInstanceId
	ParentPatternId
	ChildInstanceId
	ChildPatternId

O-ONodeChangeEvent

PK	EventKey
	RunId
	AssociateId
	InstanceId
	PatternId
	Timestamp
	LifeCycleState
	Attributes

MonitorEvent

PK	EventKey
	RunId
	AssociateId
	PatternId
	Timestamp
	ConceptPatternId
	ConceptInstanceId
	RequesterPatternId
	RequesterInstanceId

D-ANodeChangeEvent

PK	EventKey
	RunId
	AssociateId
	OmId
	PatternId
	Timestamp
	LifeCycleState
	Attributes
	InstanceType

SharedNode

PK	EventKey
	RunId
	AssociateId
	InstanceId
	PatternId
	Timestamp
	LifeCycleState
	Attributes
	Recipient
	InstanceType

OutputEvent

PK	EventKey
	RunId
	AssociateId
	InstanceId
	PatternId
	Timestamp
	Type
	Attributes

Data Analysis Toolset: Database Schema: Variables and relationships in the SQL database schema for the Data Analysis Toolset. Tables are depicted with a gray box on top of each rectangle. The primary key (EventKey) links tables together and indicates the type of event, e.g., PIED, IED, MEDEVAC. Other variables in the table represent nodes (activations) in the Observe-Orient (O-O) and Decide-Act (D-A) graphs, timing for execution of courses of action, role (i.e., S2, S3, or FSO), and other data from the Warfighter Associate.

List of Symbols, Abbreviations, and Acronyms

AI	Artificial Intelligence
AO	Area of Operations
CCIR	Commander's Critical Information Requirements
COA	Courses of Action
CPOF	Command Post of the Future
D-A	Decide-Act
DCGS	Distributed Common Ground System
FSO	fire-support officer
HVT	high value target
IED	improvised explosive device
ISR	intelligence, surveillance, and reconnaissance
KBS	knowledge-based system
MCS	Mission Command System
MEDEVAC	medical evacuation
O-O	Observe-Orient
OODA	Observe-Orient-Decide-Act
PIED	potential improvised explosive device
P-IED	potential improvised explosive device
PIR	Priority Information Requirements
POI	point-of-impact
POO	point-of-origin
ROZ	Restricted Operating Zone
TIC	Troops in Contact
WA	Warfighter Associate

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2	ARMY RSCH LABORATORY – HRED RDRL HR MP D UNGVARSKY POPE HALL BLDG 470 BCBL 806 HARRISON DR FORT LEAVENWORTH KS 66027-2302
1	ARMY RSCH LABORATORY – HRED RDRL HRM AT J CHEN 12350 RESEARCH PKWY ORLANDO FL 32826-3276
1	ARMY RSCH LABORATORY – HRED RDRL HRM AT C KORTENHAUS 12350 RESEARCH PKWY ORLANDO FL 32826
1	ARMY RSCH LABORATORY – HRED RDRL HRM CU 6501 E 11 MILE RD MS 284 BLDG 200A 2ND FL RM 2104 WARREN MI 48397-5000

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